VRIJE UNIVERSITEIT

Palaeogeographic analysis of the Dutch part of the Roman *limes* and its hinterland

Computational approaches to transport and settlement in the Lower Rhine *limes* zone in the Netherlands

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geboren te Zwolle

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Cover design: Bert Brouwenstijn

Cover photo: a route along a levee of one of the modern branches of the Rhine delta (coordinates 52.484/6.079), taken by Mark Groenhuijzen on the 9th of September 2018

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1 Introduction

One of the most challenging tasks for an archaeologist is imagining the past. In our modern society, operating in a highly anthropogenic landscape, it is difficult to visualise the social and spatial structure of societies in the past. What was the Roman landscape like? This question has often attracted archaeologists and the fact that research is ongoing continuously tells us that there is still much uncertainty involved. The Roman landscape has already been intensively studied on its many faces, such as the natural landscape (e.g. Van Dinter 2013), the cultural landscape (e.g. Vos 2009), the political landscape, the monetary landscape (e.g. Aarts 2003) or the religious landscape (Roymans 1995; Roymans *et al.* 2009, although these studies used a long-term biography approach). The 'Finding the limits of the *limes*' project is no exception, aiming at reconstructing and understanding the Roman cultural landscape of the Dutch *limes* area, specifically looking at the spatial and economic interactions between the Roman military community and the local population.

The spatial component of local-military interactions is evidently an important aspect of the research project, and it is this spatial component that will be the main focus of this thesis. The themes of this thesis will be largely related to the spatial use of the landscape in the Roman period. This is most evident in the occupation patterns of the region, which includes both military sites (forts, watch towers and camp villages) and non-military sites (towns, *vici* and rural settlements). Another important aspect of the spatial use of landscape are the road and route networks that connect these sites, through which interaction between people, both indigenous and Roman, took place. These networks of transport can occur on different levels of scale, ranging from local to interregional. Furthermore, the distribution of sites and the transport networks between sites, which can conveniently be referred to as a cultural landscape, did not occur independent of external factors. All sorts of external influencing factors can be thought of, one of which is the natural landscape, and this constitutes the first part of this thesis. The study of the spatial use of the landscape in the Roman Period can thus be broken down into a number of potential research questions that will be expressed as part of the aims of this study later in this chapter: what did the natural landscape look like? How did people occupy this landscape: what were the governing factors in the site location decision process, which factors played a role in structuring the settlement landscape? How was transport organised in the region: which natural, cultural or political aspects promoted or hindered transportation, how did the transport network structure the region?

This chapter aims at offering a background to this thesis, setting the aims of the study at hand, explaining its place within the 'Finding the limits of the *limes*' project, as well as introduce the theoretical framework upon which this study touches.

1.1 Project description

The 'Finding the limits of the *limes*' project was started in late 2012 by dr. Philip Verhagen. The principal aim of this project is to study the development of the cultural landscape in the Dutch part of the Roman Lower Rhine *limes* through spatial dynamical modelling. In particular, it is concerned with the spatial and economic relations between the local population and the Roman military population that moved into the area at the start of the Early Roman Period. Up to now the spatial economic functioning of the Dutch *limes* has mostly been studied in general terms (e.g.

Willems 1986; Kooistra 1996; Vossen 2003; Heeren 2009; Vos 2009; Groot and Kooistra 2009; Kooistra *et al.* 2013) and has only recently been subjected to more elaborate static modelling (Van Dinter *et al.* 2014).

Spatial dynamical modelling is a kind of rule-based simulation modelling that is especially suitable for exploring changes through space and time. A popular spatial dynamical modelling technique is agent-based modelling, which combines ideas of chaos theory and the agency concept. Agent-based models are thus especially suitable to study cause-and-effect chains and to explore how macro-scale patterns (which are found in the tangible archaeological material) emerge from micro-scale actions (Railsback and Grimm 2012, 10).

Agent-based modelling is therefore a useful tool to model the spatial and temporal changes in the cultural landscape of the Dutch *limes*. Using the extensive dataset of archaeological and palaeo-environmental material available in the region, rule-based models of the interaction between natural, economic and socio-cultural factors that shape the landscape can be constructed, testing different possible scenarios and archaeological theories, which in turn can be compared to the original archaeological data.

The objectives and key research questions central in this project are both methodological as well as theoretical. In the original project proposal , these questions are formulated as:

- How can we use spatial dynamical modelling to better understand the interaction between diverse but related economic activities like agriculture, animal husbandry and wood production?
- How do we translate the currently prevalent 'expert judgement' models regarding these issues into formal simulation models?
- How can we use palaeo-environmental and archaeological data to create the starting conditions and benchmarks for the models?
- What modelled socio-economic development scenarios for the *limes* area are best suited to explain the observed archaeological and palaeo-environmental record?
- What can the models tell us about the way the Romans organized the production, transport and distribution of goods needed for the military infrastructure?
- What can the models tell us about economic and social interactions between the Roman army and the local population?
- What can the models tell us about the interplay of natural and socio-cultural factors in the development of the cultural landscape?

Palaeogeography and palaeo-economy are two main components of the Dutch *limes* that are investigated separately within this project to work towards the multidisciplinary and synthesising final goals. The latter entails a study on the available archaeobotanical and zooarchaeological data to model the functioning of settlements and agricultural production, as well as the use of wood. An analysis will then be made of requirements, yields and possible surplus production in the region. Furthermore, the location and distribution of centres of production, consumption and transport are investigated. These three components combined form the palaeo-economic framework that can be used to build more complex simulation models. This study is performed by PhD-researcher Jamie Joyce (Joyce in prep.).

The palaeogeographic analysis forms another main component in this project, which is the subject of this thesis. Firstly, it is important to know the natural landscape, as it can be considered an important factor in many other parts of a simulation model, such as site location, production and transport decisions. A large part of the palaeogeographical component is concerned with the cultural landscape, analysing and modelling the spatial use of the landscape in the form of transport networks and settlement patterns. The aims of this study will be described in more detail in the next section.

1.2 Aims of this study

The primary aim of this study as part of the larger 'Finding the limits of the *limes*' project is to analyse and reconstruct the cultural landscape of the Dutch *limes* area, more specifically looking at the site and settlement patterns, the transport networks and their interrelationship with the natural environment. This has already been briefly mentioned in the earlier part of this introduction, and will be elaborated on further here.

Firstly, in order to understand spatial developments and patterns in the cultural landscape in relation to the natural landscape, this natural landscape must be accurately known first. There is a strong tradition in reconstructing the natural environment in the Netherlands, nowadays culminating in the publication of palaeogeographic maps for different time slices throughout the Holocene on a 1:500,000 scale (Vos *et al.* 2011; Vos and De Vries 2013; Vos 2015). However, these reconstructions cannot be used for detailed archaeological research since they are only intended for use on national scales. In a project modelling the carrying capacity of the western part of the Dutch *limes* in the Early Roman Period (Kooistra *et al.* 2013; Van Dinter *et al.* 2014) this problem was already recognised and resolved through the construction of a detailed (1:50,000) palaeogeographic map for this area (Van Dinter 2013). Since the current project focusses on both the Cananefatian as well as the Batavian *civitates*, the first aim is to extend this reconstruction of the natural landscape to cover the entire Dutch *limes* area. Such a reconstruction will function as a supporting dataset for further analyses of the cultural landscape and can function as an input for the spatial dynamical models developed in this project. From a more methodological standpoint however, a concern is that there are implicit and sometimes explicit uncertainties in every palaeogeographic reconstruction. A secondary aim is therefore to make these uncertainties clear and definable, and possibly test the influence of the uncertainty on further analysis.

A second aim of this thesis is a reconstruction and analysis of transport networks that were active in the region. There are many variables that make transportation a very heterogeneous part of a cultural landscape, although its spatial dispersal and often lack of archaeological deposition makes it difficult to grasp in archaeological fieldwork. Explicit transport infrastructure such as the well-known *limes* road connecting the forts along the Rhine (Van der Heijden 2016) or the recovered ships in abandoned river channels of the Rhine itself (e.g. De Weerd 1988) just represent a fraction of the transportation that must have occurred within the region. A more elaborate description of this aim is thus to quantify and make explicit the factors that govern transportation, in terms of agents, frequency, goals and modes of transport, as well as the role of the natural environment promoting or hindering transport. The results can be used for transport network reconstruction. Ideally, this would incorporate concepts of different network reconstruction methods such as least-cost paths, gravity (cost-benefit) networks and proximal point networks, in order to fully represent the dynamic governing factors of transportation. Variables used in the network reconstruction can potentially also be adapted to incorporate data from different aspects of this project, such as site production and consumption or demography. There are nevertheless methodological concerns with many, if not all, network reconstruction techniques (e.g. Herzog 2013c for optimal or least-cost paths), so another aim is to critically evaluate the application of these techniques and the use of network analysis in archaeological studies. The application of network analysis on the modelled transport networks potentially allows us to infer information about archaeological questions such as the hierarchy in settlements and the role of certain individual sites (both settlements and Roman military sites) in the network, which can be tested against archaeological evidence.

The third aim of this thesis involves an analysis of individual sites within the landscape. The analysis will involve the rural settlements on their own and in relation with the military sites. Knowing the landscape position of a site can inform us about the potential governing factors of site location decisions (for example see Van Dinter 2013, 20–22, for a qualitative approach to fort location). To achieve this, sites are firstly analysed looking at individual factors such as individual landscape components (availability of stream ridges, floodplains, etc.), access to water or to transport networks. Secondly, sites can be investigated using a multivariate analytical approach, looking at all possible governing factors simultaneously, from which information can be inferred on the relative importance of individual factors, the relationship between individual factors or the amount of variation in the site distribution that is explained by the factors under consideration. The results of the site analysis can potentially be used for further research as well, for instance functioning as a set of rules in a spatial dynamical model of settlement patterns or for investigating production capacity of individual sites based on their landscape location.

1.3 Spatial and chronological framework

As mentioned, the 'Finding the limits of the *limes*' project focusses on the region that is most easily referred to as the Dutch section of the Roman Lower Rhine *limes* (Fig. 1.1). More precisely, this study concentrates on the area that we now consider to be part of the Batavian and Cananefatian *civitates*, an area roughly bounded in the north by the former course of the Rhine (current Rhine, Nederrijn, Kromme Rijn and Oude Rijn) and in the west by the North Sea. It extends to the south up to the modern towns of Cuijk and Den Bosch just across the Meuse, which is an arbitrary line following Vossen (2003, 415), who argued that a border based on Thiessen polygons (Bloemers 1980, 155) would extend too far south and include unrealistically large parts of the sandy soils of modern Brabant, which are considered distinct from the Batavian core area, while a border on the Meuse would make the Batavian *civitas* too small (Heeren 2009, 1–2). In the east the research area extends up to the current-day German town of Kleve. In total, the area measures about 6000 km^2. Of the aforementioned boundaries, only the northern and western ones are quite well-established. The others can be considered a modern convention, based on sparse literary data and modern assumptions. It is outside the scope of this study to discuss the political or cultural meaning of the Batavian and Cananefatian *civitates* and the dynamics of tribal identity (for this discussion see Moore 2011; for a discourse on Batavian identity see Roymans 2004), this delineation of an area is considered only as a construct needed to establish a framework within which the further research takes place.

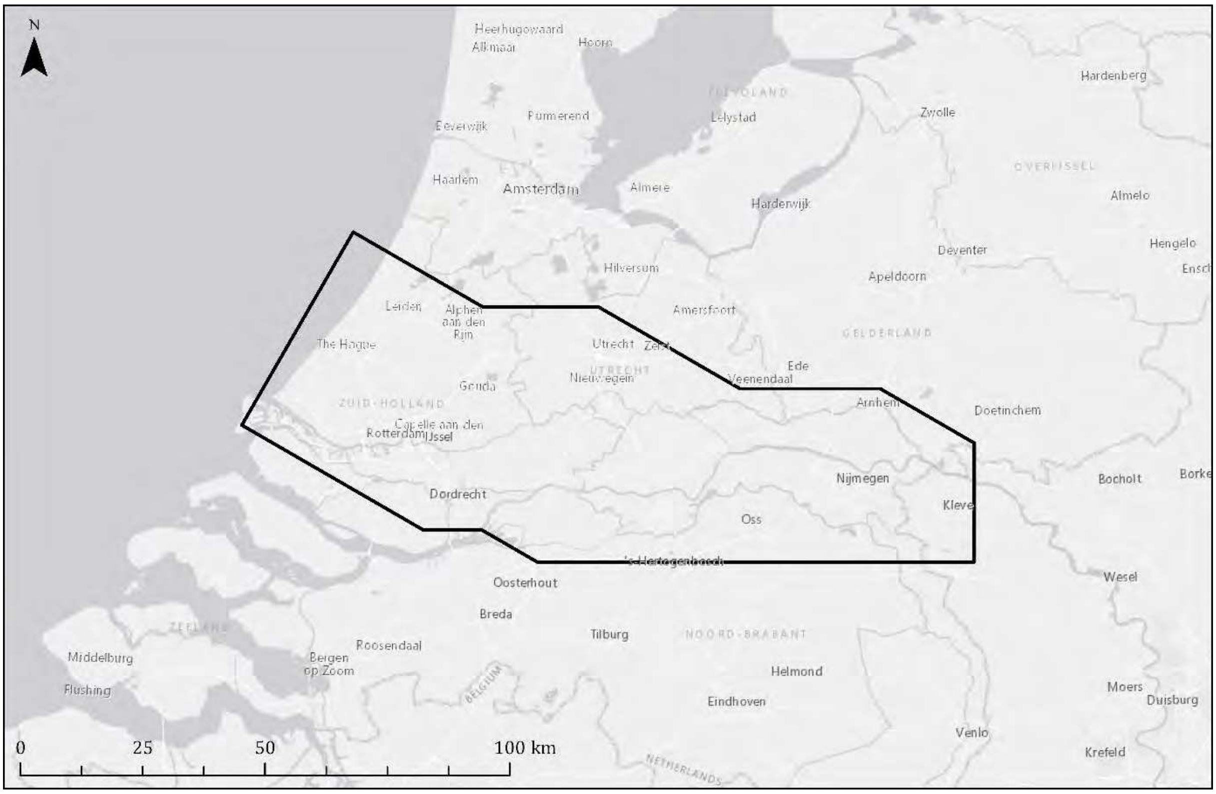


Figure 1.1. Outline of the research area on a modern topographic map.

Moreover, it must not be forgotten that the Batavian and Cananefatian *civitates* operate as part of a larger region, allowing for transfers of any kind from or to it. Both archaeological and literary data provide plentiful evidence for interregional trade contacts, social contacts, military contacts and more. In its essence, being part of the Roman Empire by definition makes every part of the empire integrated on interregional scales. Although this research might look at certain aspects of the Dutch *limes* area in isolation, it must always be remembered that this isolation is nothing more than a useful convention, and that patterns and processes, actions and decisions, are not uniquely developed within the study area but are influenced by and in turn have the potential to influence the outer world.

Chronologically, this research mostly considers the Early and Middle Roman period, beginning in 12 BC and ending in AD 270 (as defined in the ABR[1]; Table 1.1). The starting point is an obvious choice, as this was the beginning of the occupation of the Roman army at the Rhine and of the construction of some of the forts along it. This marked the start of intensive interaction between the Roman army and the local population due to their full integration in the Roman world order. The terminal point of this study can be related to this, as AD 270 roughly marks the time when the border collapsed and the forts were abandoned. Although Roman presence returned later in the 3rd century, the border forts were not generally reoccupied, making it more difficult to establish which and to what extent interaction between the Roman army and the local population occurred. It seems likely that the general structure of society was very different after AD 270 compared to the height of the Roman presence in the Early and Middle Roman Period, and therefore the Late Roman Period is taken into consideration with caution. This period lasts until roughly AD 450. Finally, if necessary (such as for comparisons with a pre-Roman situation), the Late Iron Age can incidentally be included in the research as well.

[1] *Archeologisch Basisregister* - Archaeological Reference Lists of the Netherlands.

<table>
<tr><td>Iron Age (IA)</td><td colspan="6">Roman Period (RP)</td><td>Medieval Period</td></tr>
<tr><td>800 – 12 BC</td><td colspan="6">12 BC – AD 450</td><td>AD 450 – 1500</td></tr>
<tr><td rowspan="3">Late Iron Age (LIA)</td><td colspan="2">Early Roman Period (ERP)</td><td colspan="2">Middle Roman Period (MRP)</td><td colspan="2">Late Roman Period (LRP)</td><td>Early Medieval Period</td></tr>
<tr><td colspan="2">12 BC – AD 70</td><td colspan="2">AD 70 – 270</td><td colspan="2">AD 270 – 450</td><td>AD 450 – 1050</td></tr>
<tr><td>Early Roman Period A</td><td>Early Roman Period B</td><td>Middle Roman Period A</td><td>Middle Roman Period B</td><td>Late Roman Period A</td><td>Late Roman Period B</td><td>Early Medieval Period A</td></tr>
<tr><td>250 – 12 BC</td><td>12 BC – AD 25</td><td>AD 25 – 70</td><td>AD 70 – 150</td><td>AD 150 – 270</td><td>AD 270 – 350</td><td>AD 350 – 450</td><td>AD 450 – 525</td></tr>
</table>

*Table 1.1. Time periods as specified in the ABR (*Archeologisch Basisregister - *Archaeological Reference Lists) and in ARCHIS, the Dutch national archaeological database. The Roman Period is subdivided between an Early, Middle and Late Period, which in turn are separated into two phases each. In contrast, the Iron Age is not distinguished on three levels.*

1.4 Theoretical framework

1.4.1 The concept of palaeogeography

Archaeology is inherently spatial, and it can be argued that the spatial distribution of archaeological material enlightens us in the spatial structure and the use of the spatial dimension by people in the past. For current human society, this topic is the field of study for geography. More specifically, it concerns the subfields of human geography or social geography, as opposed to the physical geography, which is the spatial study of the natural environment, whether it be geological, geomorphological, pedological, or concerns any other description of physical characteristics. The study of geography in the past can in theory be referred to as 'palaeogeography'. However, in the next few paragraphs it will be shown that this field is not delineated so clearly.

There is some ambiguity in the term 'palaeogeography' throughout different research disciplines. It appears to be most often noted as the historical counterpart to contemporary physical geography. As opposed to the reconstruction of our current environment, the term 'palaeogeography' is mostly associated with the reconstruction of the past geographic changes of long-term geological processes such as plate tectonics, for instance shown in the most recent Encyclopaedia Brittanica entry for 'paleogeography':

> ***paleogeography****, also spelled* ***palaeogeography****, the ancient geography of Earth's surface. Earth's geography is constantly changing: continents move as a result of plate tectonic interactions; mountain ranges are thrust up and erode; and sea levels rise and fall as the volume of the ocean basins change. These geographic changes can be traced through the study of the rock and fossil record, and data can be used to create paleogeographic maps, which illustrate how the continents have moved and how the past locations of mountains, lowlands, shallow seas, and deep ocean basins have changed.* (Scotese 2007)

Although this citation does elaborate most on reconstructing small-scale maps that detail changes from long-term and spatially large geological processes, the broader scope of palaeogeography, which is the ancient geography of Earth's surface, is there as well. A very similar entry is found in the Oxford dictionary of earth sciences:

> *[Palaeogeography is] the reconstruction of the physical geography of past geologic ages. A palaeogeographical map would normally show the palaeolatitude of the area under discussion together with the location of inferred shorelines, drainage areas, continental shelves and depositional environments. At the present time the base map would normally be a reconstruction based on palaeomagnetic data (see palaeomagnetism), although many maps in earlier publications used the present geographical positions of the continents as a foundation.* (Allaby 2013)

Especially in the context of the Dutch landscape however, palaeogeography has long been used to describe a field also focussing on changes in the physical landscape on more detailed timescales and spatial scales, as attested by this passage on the discipline of palaeogeographic reconstruction, taken from a Dutch publication:

> *[A palaeogeographic reconstruction] is a map view of the distribution of deposits, depositional environments and landforms at a given time in the past.* (translated from Zagwijn 1986, 7)

Concluding from this variety of definitions, palaeogeographical reconstruction in the broader sense is not limited to specific scales. It is roughly subdivided into different scale levels in the first version of the Dutch Archaeological Research Agenda (NOaA) (Deeben *et al.* 2005, 2), although the boundaries are not always well-defined. This subdivision is given in Table 1.2.

Area	**Scale level**	**Area**	**Map scale**	**Archaeological entity**
Local	Micro	<5 km^2	Up to 1:10,000	Site and surroundings
Regional	Meso	5-5,000 km^2	1:10,000 up to 1:100,000	(Archaeo)region
National	Macro	5,000-35,000 km^2	1:100,000 up to 1:1,000,000	Netherlands
(Sub)continental	Mega	>35,000 km^2	Over 1:1,000,000	Northwest-Europe

Table 1.2. Scales and their associated characteristics identified in Dutch palaeogeographic research (adapted from Deeben et al. *2005, 2).*

It becomes clear that 'palaeogeography' is a concept in common use for referring to the reconstruction of the natural environment in the past. As has been briefly mentioned in the beginning of this chapter, the natural environment is one of the topics that will feature in this study. However, it can be argued that the term 'palaeogeography' itself is too exclusive, and does not relate well to contemporary geography, comparing for example the Encyclopaedia Brittanica entry:

> ***geography****, the study of the diverse environments, places, and spaces of the Earth's surface and their interactions; it seeks to answer the questions of why things are as they are, where they are. The modern academic discipline of* ***geography*** *is rooted in ancient practice, concerned with the characteristics of places, in particular their natural environments and peoples, as well as the interrelations between the two.* (Johnston 2017)

Contemporary geography is not limited to the natural environment, but also incorporates a social or cultural component, and so palaeogeography could also be seen as a larger encompassing concept. Connecting the cultural landscape with the natural landscape is one of the archaeological themes in this study, and thus it can likewise be referred to as palaeogeography, i.e. the geography of the past. On a side note, it might be argued that 'palaeo-' is generally used to refer to the ancient past on geological timescales, and that a more commonly used and thus more appropriate prefix would be 'archaeo-'. Although attempts have been made to popularise 'archaeogeography', it appears to remain confined to French academic archaeology (e.g. Chouquer 2008). The next sections will outline the history and theoretical frameworks and developments of both the more common 'physical' palaeogeography and what can potentially be referred to as 'archaeological' palaeogeography.

1.4.2 Physical palaeogeography

The mapping of our physical environment has long been an interest to generations of scientists, working professionals and the general public. Since ancient times, there has been a need to map landscape elements and characteristics for various purposes such as quarrying expeditions, as attested by the Turin Papyrus Map drawn around 1160 BC (Harrell and Brown 1992a), arguably the oldest geological map known. Probably created by the 'scribe of the tomb' Amennakhte, this map depicts the landscape as it was perceived to the naked eye, with different colours representing the varying geology of the hills and wadi alluvium in the Wadi Hammamat region in Egypt (Harrell and Brown 1992b).

Since then, most maps have been of a more topographical nature, describing the locations of towns, cities, roads, or natural elements such as waterways, lakes, hills and dunes. Some maps can also include other useful information about the physical landscape, such as the depiction of areas prone to flooding on the Low Countries' city maps made by Jacob van Deventer between 1559 and 1575 (Rutte and Vannieuwenhuyze 2018). Although this distinction had a militaristic purpose at the time, it nowadays gives us an indication of the relative elevation of the landscape around the cities. These maps can also include other interesting landscape features, such as remains of abandoned stream channels. Because Van Deventer made use of the then relatively young technique of triangulation, the location of all these landscape elements in reference to known landmarks (such as churches) are considered fairly accurate (Karrow 1993, 151).

Large-scale mapping of a purely geological nature did not take a large flight until the famous work of William Smith on England and Wales in 1815 (Smith 1815; 1820). The oldest geological overview maps also featuring the Netherlands were produced by Keferstein (1821) and D'Omalius d'Halloy (1822; 1828), although neither mapped any variation within the Quaternary deposits. The first detailed geological map in the Netherlands was published by Acker Stratingh (1837), describing the province of Groningen. This was followed up by a geological overview map of the Netherlands at a scale of 1:800,000 by Staring (1844), subdividing the younger strata into different depositional categories. Staring subsequently produced the first series of overview maps of the surficial geology at a scale of 1:200.00 between 1858 and 1867 (Staring 1858).

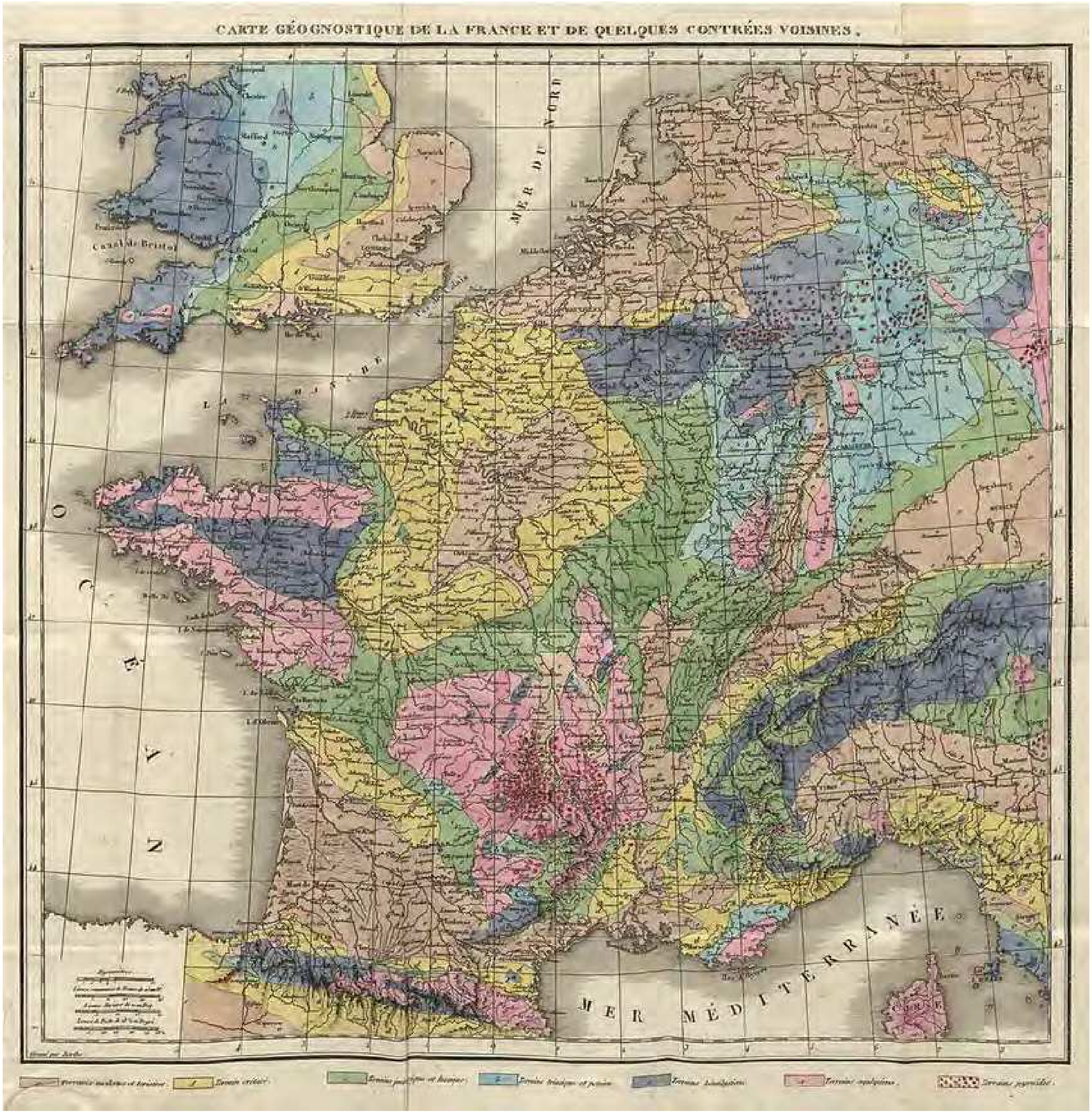


Figure 1.2. Geological map of France, the Low Countries and neighbouring areas published in 1835 (first version published in 1822) by D'Omalius d'Halloy (from Lutz and Lorenz 2013).

Geological mapping of the Netherlands was repeated with varying success (cf. Berendsen 2007) on a scale of 1:50,000 in the first half of the 20th century (Tesch 1942) and in the 1960s and 1970s using a renewed profile-type legend (Hageman 1963a; 1963b). Meanwhile, national soil mapping and geomorphological mapping programs were also carried out between 1965 and 2003 (published digitally in Alterra 2006; resp. Alterra 2008). A further useful development is the introduction of the AHN[2] digital height model, constructed using laser altimetry. Initially the AHN was delivered in a 5×5 m grid with a vertical standard deviation of 15 cm (Rijkswaterstaat-AGI 2005), but in the newer version (AHN2), which was used for this study, this was improved to a grid of 0.5×0.5 m (Rijkswaterstaat-AGI 2013; Van der Zon 2013). The newest version (AHN3) has been in development since 2014 and from 2019 will cover the Netherlands entirely.

[2] *Actueel Hoogtebestand Nederland* – Up-to-date Height Model of the Netherlands

The previous paragraphs dealt with the mapping of the contemporary physical environment. Research in physical palaeogeography, most commonly under the general term 'palaeogeography', has been carried out in the Netherlands for a few decades. Very often this occurred on limited spatial extents, limited to certain landforms or depositional environments, and limited within specific time-frames. Good examples include (but are not limited to): Wiggers (1955) on the Noordoostpolder region; Pons (1957) on the eastern river area; Pons et al. (1963) on the Holocene North Sea coast; Jelgersma *et al.* (1970) on the coastal dunes; Zagwijn (1971) on the Oer-IJ estuary; Van de Meene and Zagwijn (1979) on the Rhine course in Germany and the Netherlands; Griede and Roeleveld (1982) on the northern coastal area; and Berendsen (1982) on the central river area. Not all of these studies have the primary aim of producing palaeogeographic reconstruction maps, but rather aim at improving the understanding of processes in the landscape or the evolution of a specific element in the landscape. Maps that were produced during these studies could depict (parts of) the landscape at different points in the past, or they could be single anachronous map that depict the evolution of a specific landform (such as a river or coastline) over time, leaving out the palaeogeographical evolution of parts of the landscape that are not under investigation. Because of the specific aims and research questions of these studies, there is often no necessity to apply a palaeogeographical reconstruction on a wider scope. In nearly all cases the scale at which the palaeogeographic reconstruction was applied is no greater than 1:25,000, probably due to limitations on data availability, limited means to process the data towards creating coherent maps, but perhaps more importantly because introducing more spatial detail had no more added value to the various research goals within these studies.

Palaeogeographical reconstruction for the entirety of the Netherlands has been explored by Zagwijn of the Geological Survey, resulting in the construction of a series of twelve palaeogeographical maps of the Netherlands for the Quaternary (Zagwijn 1974). Of these twelve maps, two concerned the Holocene, roughly depicting the landscape around 7000 and 4300 years BP. A series of ten palaeogeographic maps limited to the Holocene were published by the same researcher over a decade later (Zagwijn 1986), that besides being more detailed in time intervals also showed more spatial details. It is based on a large number of smaller studies, some of which have been mentioned in the previous paragraph, on more general geological and geomorphological studies, as well as on the geological maps at scale 1:50,000 and the accompanying explanations. The palaeogeographic maps were constructed at a scale of 1:500,000 in a schematic way, which makes them suitable for understanding long-term developments and areas in a wider context, but less suitable for use on regional and local scales. More recently, a new series of palaeogeographic maps have been developed for the Holocene (Fig. 1.3; Vos *et al.* 2011). The aim of this map series was to revise the map series by Zagwijn in more detail, based on recent insights and developments in geology, physical geography and related fields. Among the sources used are a number of recent regional palaeogeographic studies, some of which in turn are based on or continuations of older palaeogeographic studies mentioned before.

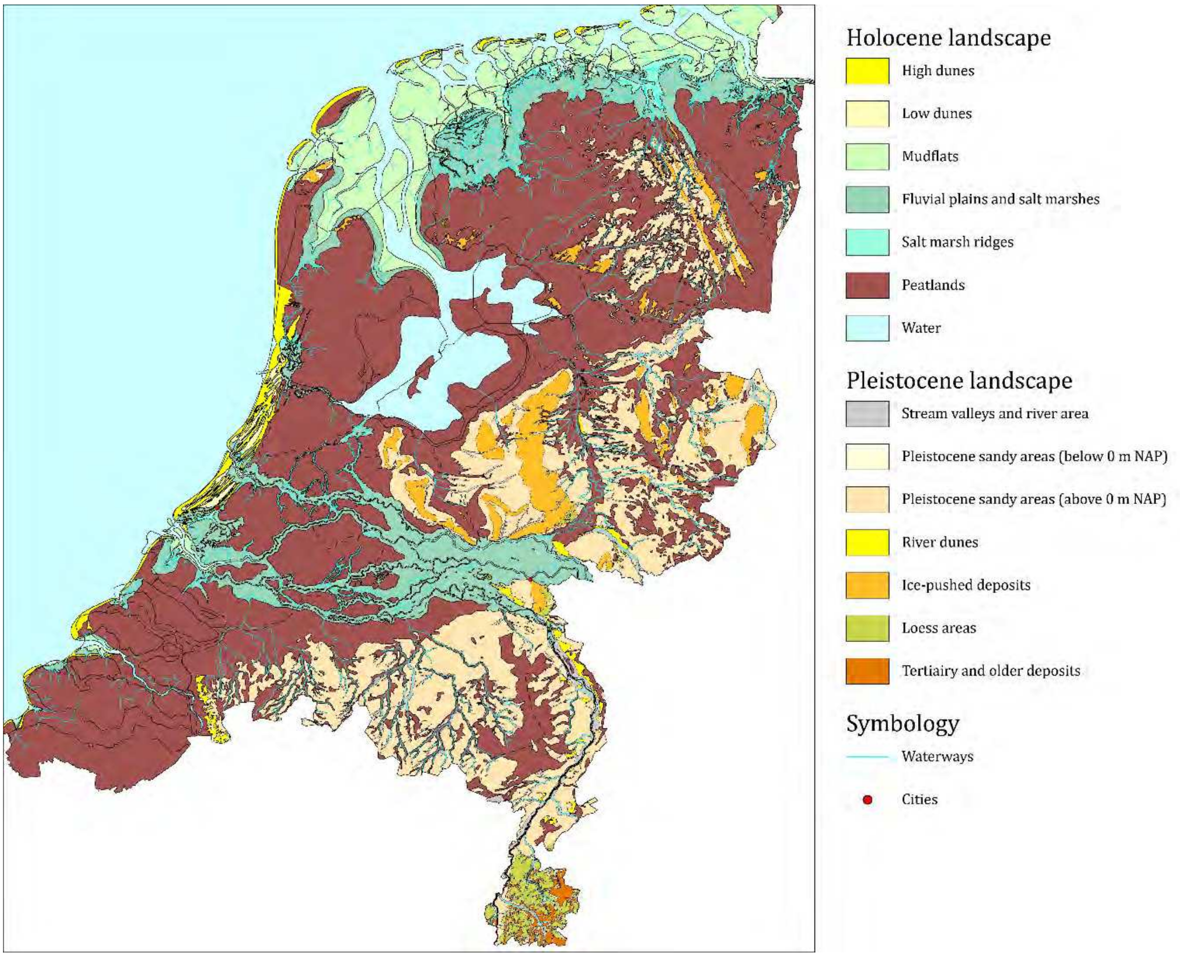


Figure 1.3. Palaeogeographic reconstruction of the Netherlands around AD 100 (from Vos and De Vries 2013).

One notable addition is the long-running study on the Rhine-Meuse delta by a research group from the University of Utrecht. The first notable result is the PhD-thesis of Berendsen (1982) on the genesis of the landscape in the southern part of the province of Utrecht. Along with these thesis came five detailed geomorphological maps, based on approximately 90,000 corings. The research in the Rhine-Meuse delta was continued, which resulted in the 2001 landmark publication on the palaeogeographic development of the Holocene Rhine-Meuse delta (Berendsen and Stouthamer 2001). Since the initial publication by Berendsen in 1982, a number of PhD-theses and postdoc projects have increased the understanding of the architectural build-up and formative processes of the Rhine-Meuse delta (see Berendsen 2007, 172 for an overview). An update of the palaeogeographic reconstruction of the Holocene Rhine-Meuse delta was presented in 2012 (Cohen *et al.*, 2012).

The use of palaeogeographic maps in archaeological research is a relatively young development. Earlier studies either reconstructed the natural environment on a site-basis (e.g. Bennema and Pons 1957), or investigated a site and settlement pattern using contemporary physical geographical data (e.g. Bakels 1978). Examples of the production of physical palaeogeographic maps with a specific archaeological purpose are of more recent date, such as Vos and Van Heeringen (1997) on Zeeland in the Holocene; Fokkens (1998) on the Frisian-Drentian plateau between 4400 BC and 500 AD; Vos and Gerrits (2005) on the Westergo region between 600 BC and 500 AD; Dijkstra (2011) on Southern Holland in the Early Medieval Period; and Van Dinter (2013) on the Old Rhine region in the Netherlands in the Roman period. Although the scale is often still set at 1:50,000 (limited by the scale of the sources used), because of the direct application of

GIS the mapping is done in a much less schematic way and allows the map to accommodate a more differentiated subdivision compared to earlier palaeogeographic reconstructions and also to be customised for specific (archaeological) research questions.

1.4.3 Landscape archaeology

Archaeological papers rarely (if ever) practise the term archaeological palaeogeography. If it were in common use, it can be imagined that this field should concern itself with the spatial distribution of human populations in the past and their remains in the archaeological record. In the more practical sense of this thesis, primary interest lies then in research regarding spatial patterns of habitation and movement, which are reflected in the archaeological record through larger and smaller settlement sites and remains of infrastructure, or which might not be reflected in the archaeological record at all. In archaeology, this research generally belongs to the field of landscape archaeology.

Landscape archaeology nowadays is a very comprehensive field. In the most literal sense, landscape archaeology is concerned with the relationships between man and the landscape in the past. Although this might appear to be quite clear, there is much ambiguity involved, leading to different landscape archaeological approaches thriving within different theoretical schools.

Firstly, there is ambiguity in what the relationships between man and the landscape are. This can perhaps best be explained in the context of the general paradigm shifts in archaeological theory, since landscape archaeology is noted to have closely followed the developments in the general theoretical and philosophical debate in archaeology (Darvill 2008, 60). Starting in the latest phases of the cultural-historical tradition that was prevalent prior to the 1960s, landscape began to feature as a backdrop to archaeological research, such as the pioneering work on the incorporation of ecological setting, vegetation history and lake stratigraphy in the archaeological investigations by Clark on Star Carr (Clark 1954). Two generally opposing approaches of the use of landscape in archaeology surfaced in the first half of the 20th century, namely physical-geographical determinism and the cultural landscape approach. The former is inspired by 19th century geographers such as Ratzel (1882) who believed that human behaviour was largely shaped by the physical landscape. The latter originated in geography as a response to that and is attributed for a large part to Sauer (1925). It can be seen as an opposite as it is based on the premise that man shapes and structures its surroundings rather than being governed by it, thus defining the cultural landscape. This dichotomy in the days of proto-landscape archaeology already exemplified the contrasting ideas regarding the role of landscape in the relationship with humans in the past.

There is a change in archaeological theory in the 1960s that is noted as the onset of New Archaeology, later also known as processual archaeology. Archaeological research in general moved away from classification in cultural-historical context, but aimed to answer specific questions of humans and society in the past using scientific methodological research designs (Binford 1964). Already in the early days of this paradigm shift, it is noted that regional approaches are most appropriate for studying cultural processes (Binford 1964, 440). The application of spatial analysis took a flight, such as the work by Hodder & Orton (1976) promoting quantification of spatial patterning and the application of statistical methods, also borrowing concepts of geography including Christaller's (1933) Central Place Theory.

In Dutch archaeological research, New Archaeology only partially managed to infiltrate mainstream research. This may be attributed to the field-oriented, soft (natural) scientific and a-theoretical character of Dutch archaeological research at that time (Louwe Kooijmans 1994, 43;

Slofstra 1994, 16). In the 1960s Dutch archaeology was split into two schools: that of a 'cultural-historical' approach, and that of an 'ecological' approach. The latter was rooted in the natural-scientific and environmental approaches of Van Giffen, and as such its adherents were more susceptible to adopting approaches from New Archaeology. An example proposed by Slofstra (1994, 18) is the Assendelver Polder project of the University of Amsterdam that started in 1978, and largely followed the research design laid out by Flannery (1976) in his multiscalar spatial analytical research on the Peruvian Oaxaca Valley to investigate the relations between settlement patterns and the environmental setting. However, Louwe Kooijmans (1994, 44) argues that these studies were not fundamentally different in their methods and research problems from earlier archaeological studies from the 'ecological' school. Instead, he posits that the post-war research tradition in the Netherlands was a fertile ground for the opportunistic selective reception of ideas from New Archaeology, with researchers entering the middle ground between the already existing 'a-theoretic' (cf. Louwe Kooijmans 1994, 44) schools and the theory-laden processual approaches (e.g. Bakels 1978; Bloemers 1980). In similar fashion, Härke (1994, 36) remarks that Dutch archaeology managed to attain a position between the solid and methodical approaches to archaeological evidence akin to the German school (including the adoption of methods from the *Archaölogische Landesaufnahme*) and the more theoretically inclined approaches of the British school of archaeology.

After the turn of the 1980s, an increasing number of archaeologists voiced criticism of the framework of processual archaeology, notably in a collection of works edited by Hodder (1982a). This work is seen as the start of a new movement that would later be called post-processual archaeology (Renfrew 2007, 222). The main critique of post-processual archaeologists is that archaeology should take greater account of meaning, the individual, culture and history (Hodder 1984, 30), in other words: culture is not just a means of adaptation but a meaningful construction (Hodder 1982b, 13). This also had its effect on landscape archaeology, as the notion arose that landscape is not always tangible but can also be seen as 'qualitative, experienced, contextual, relative, temporal and dynamic' (Tilley 1994, 14). While post-processual landscape archaeology gained a large following and also impacted Dutch regional archaeology (e.g. Roymans 1996b for the theoretical developments in the Southern Netherlands project), critique has been voiced on aspects such as the lack of a practical methodology (Fleming 2006, 279). Attempts have been made to bridge the gap between different perspectives (e.g. Johnson 2007), and it has also been rightfully noted that different approaches to landscape are not mutually exclusive in the study of landscape (Witcher 1999, 13–14).

Returning to the definition of landscape archaeology, there is clearly also a difference in what 'landscape' actually means. In the introduction to the proceedings of the first international conference on landscape archaeology, the definition of landscape is seen as one of the shaping factors of the different schools working in landscape archaeology (Kluiving and Guttmann-Bond 2012, 14). The authors highlight two definitions of landscape, following a paper by Olwig (1996) exploring the meaning of landscape and its implications for the relations between nature and society. In the first place there is the definition of landscape as a territory with all its included institutions, which is subjective but can be studied objectively through fieldwork and archival studies (cf. Renes 2011, 138). The second definition defines landscape following the work of the Dutch landscape painters of the 16th and 17th century; that is the landscape that man perceives, or more elaborate: the landscape that is created in the mind of the observer (cf. Renes 2011, 138). It is argued that the former definition has been practiced by processual archaeologists, historical geographers and physical geographers, while the latter was adopted mostly by post-processual archaeologists, cultural geographers and social scientists (Kluiving and Guttmann-Bond 2012, 14).

It is clear that landscape archaeology is concerned with the landscape and man in the past, although the object of study and the way in which it is studied is different. It could be argued that the ‘Finding the limits of the limes’ project, which aims to quantify and model spatial cultural and economic relations, falls perfectly in the tradition of processual archaeology. However, the use of the concept of agency in agent-based modelling emphasis the role of the perception and decisions by individuals, for which processual archaeology was often found lacking (Johnson 1989, 191). Moreover, simulation modelling is not necessarily environmentally deterministic; through interaction between agents and the introduction of rules derived from social structures, political structures or other intangible concepts (for instance the ‘mythical’ landscape of Roymans (1995), which can potentially be modelled using historical and archaeological evidence), it is possible to model the cultural landscape including the human perception of it.

1.4.4 Sites and settlements

Early archaeological research in the Netherlands, as much as elsewhere in the world, was mostly incidental in nature, composed of stray finds and small isolated excavations. Except for some early observations, such as by Heldring (1838; 1839), archaeological research looking at regional patterns was not really undertaken in the Netherlands until the pioneering work of Modderman, who was interested in finding the so-called ‘habitation soils’ (Dutch *woongronden*; Fig. 1.4.). He accompanied the soil mapping campaigns in the late 1940s and early 1950s in the eastern river area and identified habitation soils subdivided by archaeological period, with a large part of this work dedicated to Roman habitation soils (Modderman 1949b; 1949c; 1950; 1951; 1953). Already noted was the strong relationship between these archaeological sites and the natural environment (Modderman 1948, 210).

Figure 1.4. The mapping of Roman habitation soils in the Betuwe area (eastern Dutch river area). Legend (top to bottom): Pleistocene soils; fluvial levees; floodplains; splay deposits; old channel belts; primarily native find material; primarily Roman find material; native and Roman find material (from Modderman 1949c).

Modderman already made a bold statement regarding the completeness of the archaeological dataset, stating that regarding the Betuwe area in the Roman period not many sites are left undiscovered (Modderman 1949c, 68). Willems debunks this statement to some extent, calculating that a later survey in the Betuwe (Havinga 1969) showed that about 20% of sites were missed, and further states that on average 10-15% of the sites of the Batavian area remain undiscovered (Willems 1986, 75). Reasons for this are a random error due to the difficult recognition of sites or the low sampling density, and a systematic bias for sites which have a sediment cover thicker than the vertical depth of the soil survey (1.2 m at the time) (Willems 1986, 73). Furthermore, the effects of river erosion, especially for the eastern river area, must not be underestimated when trying to estimate the original dataset size. Interesting in the aspect of the archaeological dataset is the work by Vos (2009), who performed a reconstruction of Roman settlements locations through reinterpreting data from the national archaeological database (ARCHIS). A similar method was applied by Vossen (thesis unpublished; see also Vossen 2007) for the whole Batavian *civitas* and by Van Dinter *et al.* (2014) for the Cananefatian part of the *limes*.

The general structure of the military sites in the Netherlands is quite well-known (Fig. 1.5). Especially the locations of *castella* in the western river area are well-established, while the eastern part has considerable problems with river erosion that make it impossible to establish if current interpretations of the *castella* locations hold (this ties in with the discussion on Roman toponyms and the reconstruction of the military road, section 1.4.5). Previous researchers thought that the *castella* were located on the higher points of the landscape (Bechert and Willems 1995), although careful analysis has shown this to be the opposite for the majority of sites (Van Dinter 2013, 20). Van Dierendonck (2004) considers the presence of smaller military structures such as watch towers unlikely, although Van Dinter (2013, 25–26) argues that they were an integral part of the early defence system with intervisibility being of primary importance, also taking into account the discovery of multiple watchtowers near the *castellum* of De Meern (Langeveld *et al.* 2010a).

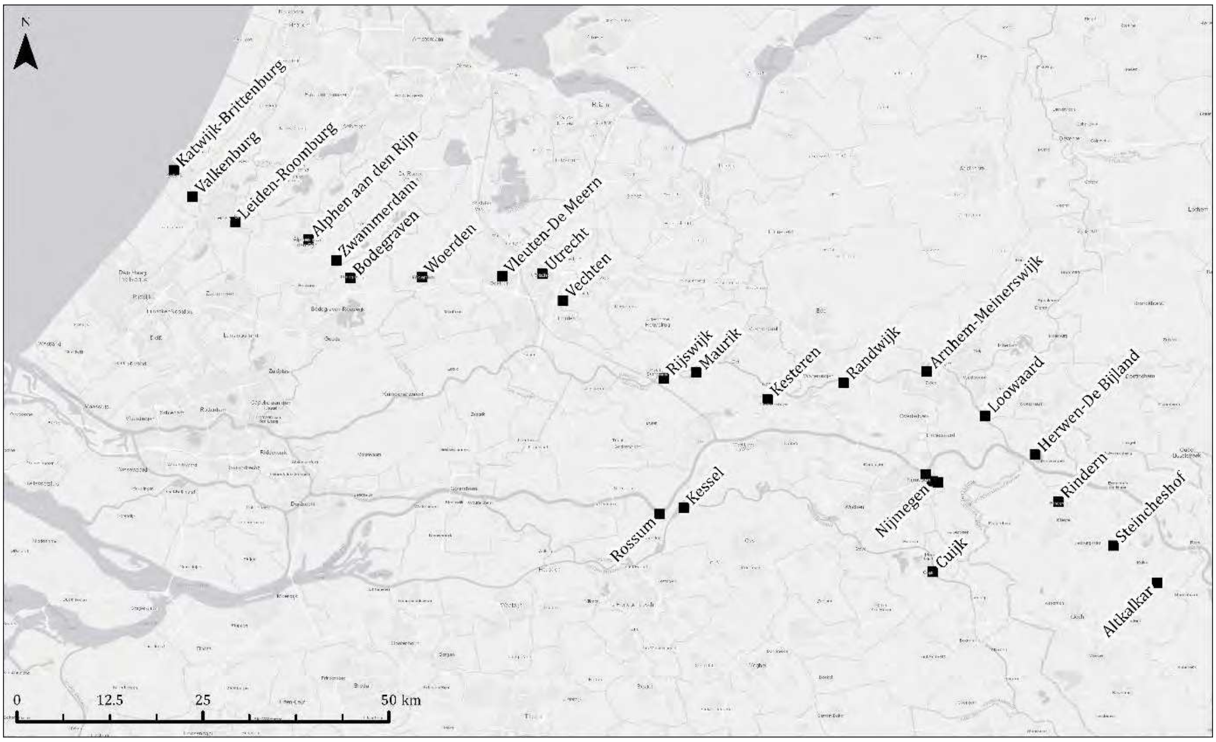


Figure 1.5. Diachronic overview of Roman fort locations in the Netherlands and nearby Germany, labelled with their common modern toponyms.

As was noted in section 1.4.3, archaeologists' interests in finding patterns and logical order in regional systems was already a long-standing tradition in archaeological research, and was somewhat reinforced through the processual research school, in the Netherlands especially since the late 1970s. Reconstructions of settlement patterns, land use and analysis of site locations were performed using concepts of geography such as Central Place Theory (Christaller 1933), Von

Thünen's (1826) model of agricultural land use, Thiessen polygons (Thiessen 1911, although the method was already known in mathematics as Voronoi diagrams) and concepts such as site territory or 'catchment' (cf. Vita-Finzi and Higgs 1970). Some of these concepts, particularly those related to site location in relation to the environment such as site catchment models are related to the general trends in landscape archaeology.

Early researchers in Dutch archaeology that adopted methods from the processual school are Bakels (1978; joining it with the traditional 'ecological' school) with a study on Linearbandkeramik settlements in relation to the natural environment using Thiessen polygons and the site catchment concept, and Bakker (1982) on Funnelbeaker settlement patterns. Regional research projects in a processual framework ongoing in the Netherlands at the time very much tied in to the settlement pattern research, as has been mentioned for the Assendelver Polder Project (section 1.4.3) but also in the South Netherlands project (e.g. Theuws 1989 on a medieval rural settlement system). Although the very deterministic studies and concepts such as site catchment were generally abandoned by post-processual thinking which favoured ideological or social approaches to landscape, it must be argued that both approaches are not mutually exclusive, and especially in the context of simulation modelling (see also section 1.4.6.7) can be unified in a holistic approach to the functioning of the cultural landscape. Recent research has shown that the interest in the traditional site analytical approaches has not died out in the Netherlands (Jeneson 2013), nor abroad (Goodchild 2007). Other statistical techniques applicable to site analysis have also returned in popularity, such as multivariate approaches (e.g. Fernandes *et al.* 2011; Vandam *et al.* 2013), that often account for both natural environmental as well as social and cultural factors.

A logical development in the study of settlement patterns is the construction of models that quantitatively predict the ordering of settlement location within the landscape. This is the technique known as predictive modelling. Its concepts and history are concisely outlined in Verhagen (2007, 13–25). In general, predictive modelling aims to predict the locations of archaeological sites in a region based on a site sample or fundamental notions of human behaviour (Verhagen 2007, 13; cf. Kohler and Parker 1986, 400). These two approaches can also be captured in the terms 'data-driven' or 'theory-driven' respectively, although both approaches are not necessarily mutually exclusive. In the Netherlands the earliest example of predictive modelling is a study by Brandt *et al.* (1992) on archaeological sites between the Palaeolithic and Middle Ages in the Regge Valley (eastern Netherlands). Subsequently, the technique has found most use in commercial archaeological practice, as predictive models of site location are relatively cost-efficient in comparison to other exploratory techniques.

1.4.5 Transport

Not surprisingly, Modderman was also one of the first to propose an approach for investigating regional infrastructural patterns, primarily related to the main *limes* road which connected the castella and vici along the border and extended into the hinterland (Modderman 1952). The reason why research has focussed on this military road is that it is one of the earliest (land-based) regional transport phenomena for which we expect to recover archaeological material, and because we are also provided with historical sources that document (travel along) these roads; well-known are the Peutinger Table (Talbert 2014) and the Antonine Itinerary (Cuntz 1929). For comparison: when investigating prehistoric routes, the primary concern is not with archaeological material, as these roads are often not roads in a modern physical sense. In prehistoric times, routes can be better approached as social or mental concepts, being governed by the social or economic structure and the natural environment but not necessarily 'set in stone'.

Similarly, smaller and more local roads contemporary to the Roman military roads also do not leave archaeological or historical traces and can only be 'rediscovered' by investigating the possible factors that structured these connections between places. Willems (1986, 63–64) offers a useful distinction between 'roads' and 'routes', whereby roads are only spoken of when there are physical indications of the presence of a road, while a route is only used to indicate a reconstructed connection between places that is assumed to have been present. This distinction is different from what is used in studies that use the road system for (qualitative or quantitative) analysis, which subdivide roads based on their function (e.g. Chevallier 1972, 68–70, who distinguishes public/military, local/regional and private), independent of the material remains.

As said, the presence of archaeological as well as historical evidence had the effect that most studies are focussed on reconstructing, analysing and interpreting the main roads of the Roman road infrastructure. Studies involving a variety of aspects of the (use of the) Roman military and public road on empire-wide scales are performed with some frequency, examples include a typology of travel (Chevallier 1988); cultural change through changing mobility (Laurence 1999); transport and information transfer (Kolb 2000); and most recently a model of a path-finding network of the Roman empire (Scheidel *et al.* 2012; Scheidel 2014).

Research on the Roman road in the Netherlands has been largely aimed purely on reconstructing the Roman *limes* road, sometimes tied in with an interpretation of the Roman toponyms known from the literary sources (e.g. Verhagen 2014). The principal routes in the Dutch *limes* area are in general terms well agreed-upon (see Willems and Van Enckevort 2009, 66–67 for a rough reconstruction), with the main military road connecting the fortresses following the south bank of the Rhine from the capital of Germania Inferior (Cologne) to the North Sea coast near Katwijk. This is especially aided by the knowledge of the locations of the *castella* and the finds of material remains of the road. However, small deviations of where the actual road was located are still possible, for instance comparing Hessing *et al.* (2006) and Vos (2009) for the Kromme Rijn area. A good overview for the state of knowledge for the Cananefatian *civitas* is Luksen-IJtsma (2010). However, from this work it also becomes clear that this route is not necessarily static and unique, but may consist of multiple roads (e.g. a connection to the fort and a short-cut avoiding the fort) or may be moved through time through factors such as river erosion. There are more questions surrounding the exact route of the military road in the Batavian *civitas*, partly due to the uncertainty on the completeness of the archaeological record of *castella* and partly due to the difficulty of connecting the literary evidence to these *castella* sites (compare Bechert and Willems 1995; Joosten 2003; Buijtendorp 2010, 714–729; Verhagen 2014; Verhagen and Heeren 2016). An overview of Roman roads in the entire Netherlands is provided by Van der Heijden (2016; Fig. 1.6).

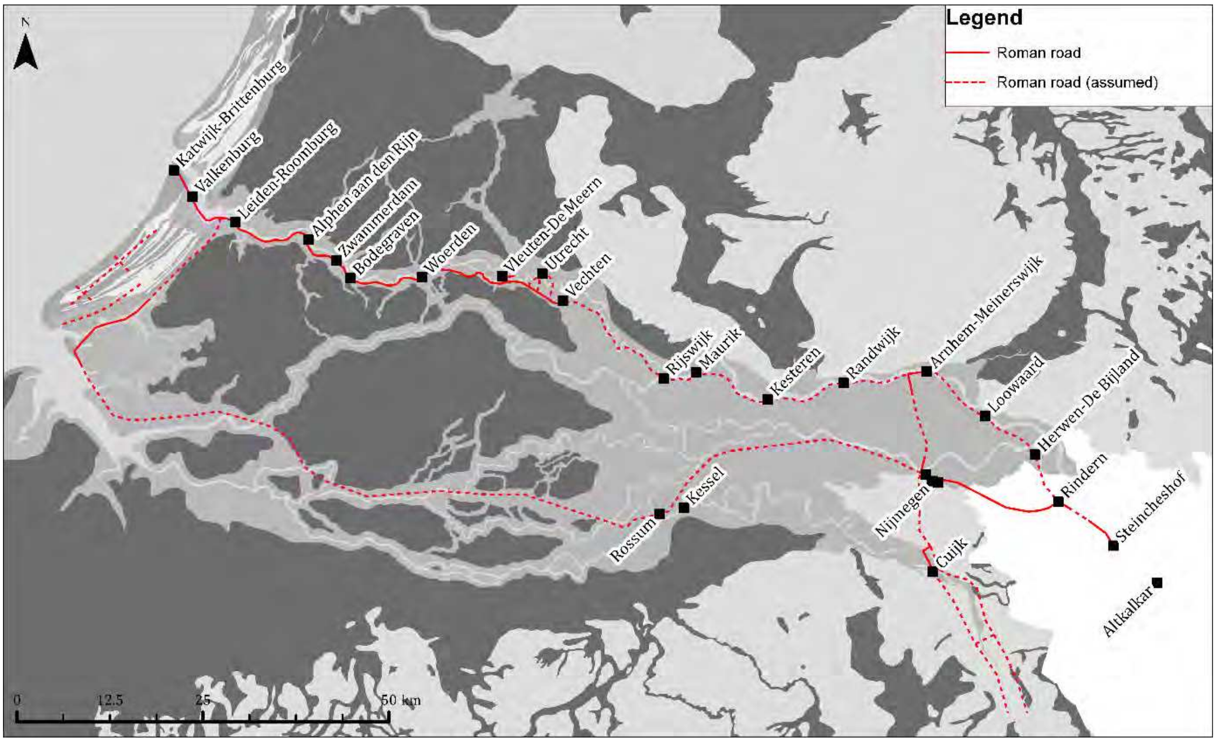


Figure 1.6. Overview of Roman roads in the Netherlands (based on Van der Heijden 2011; 2016; Van Dinter 2013). The palaeogeographic reconstruction of AD 100 is used as background (adapted from Vos and De Vries 2013).

Little research has been done regarding the non-major routes in the Netherlands, which can at least partly be attributed to the likely immaterial nature of most of these connections. How land transport was organised and carried out is also relatively unknown, particularly for a 'peripheral' region such as the Dutch river area, which outside the main roads also offered major environmental constraints for traditional land transport as it is known for instance from Roman Italy and Gaul (e.g. Chevallier 1988).

Obviously transport in Roman times was not limited to land transport, and this is most certainly the case for the Batavian and Cananefatian *civitates*. Van Dinter (2013, 25) notes that the positioning of the *castella* is specifically aimed at controlling water transport across the Rhine and its (dis)tributaries, emphasising the importance of the water arteries in transport. Regarding infrastructural works, we know of at least two canals. Apart from the written sources, Corbulo's Canal is well-known from archaeological research, connecting the Rhine and Meuse through Forum Hadriani (Voorburg), although it appears to have connected two existing tidal creeks rather than being an entirely artificial connection (Hazenberg 2000, 34). The location of Drusus' Canal (or Canals) is still debated, although the originally most popular hypothesis, a connection between the Rhine and Oude IJssel, has been disproven (Makaske *et al.* 2008). Other archaeological material related to water transport include revetments, quays or mooring stages close to a number of *castella* (cf. Van Dinter 2013, 20, citing other sources) and harbours such as recently excavated in Voorburg (Driessen and Besselsen 2013). Furthermore, a number of ships have been found in the Dutch river area, most notably the Zwammerdam-type barges from Zwammerdam (De Weerd 1988), Woerden (Blom and Vos 2008), De Meern (Jansma and Morel 2007; De Groot and Morel 2007) and Druten (Lehmann 1978). Traditionally it was thought that these ships were used as one-way transport: they were supposed to be constructed in the Middle Rhine region (modern Germany) used for transport to the Lower Rhine region (or Britain) and subsequently disposed of. However, recent research on these barges, notably the ship known as 'De Meern 1', has shown that there are several possibilities for upstream transportation (Jansma and Morel 2007, 151–174). Besides the large ships, personal and commodity transport on the river also occurred on smaller scales, attested by the dugout boats found in Woerden and De Meern.

Unfortunately, most research regarding the organisation and functioning of water transport has focussed on the Mediterranean. Yeo (1946) for example started a tradition (see Duncan-Jones 1974; Arnaud 2007; Scheidel 2013) of estimating the costs of water transport versus land transport using Diocletian's Edict on Prices and other literary sources. Although these analyses can include river transport to some extent, they often not account for the difference between upstream or downstream transport nor accommodate short-haul transport or transport using less-navigable rivers and lesser known transport modes (such as dugouts, known also as dugout canoes, logboats or German *Einbaumen*; Maarleveld 2008).

Transport in the Roman Empire can potentially be approached as a network. In essence, a network is a collection of nodes and links (or arches) (Knappett 2013a, 3). The methodological advantages of a network approach in archaeology are seen as 1) an obligation to consider relations between entities; 2) an inherently spatial dimension that can be both social and physical; 3) a strong method for articulating scales; 4) the ability to incorporate both people and objects; and 5) the ability to include a temporal dimension (Knappett 2011, 10). Inspired by research in New Geography (e.g. Haggett and Chorley 1970), early adopters in archaeology have found networks as a useful tool to understand connections between people (e.g. Clarke 1972; Irwin-Williams 1977). More recent work has drawn mostly from Social Network Analysis (Carrington *et al.* 2005). Brughmans (2013b) presents an elaborate overview of the application (and ignored aspects) of this approach in archaeological research.

There are several ways to reconstruct a network using an archaeological dataset. Firstly, the decision must be made what the nodes and the arches should represent. This is very much the first theoretical preconception that is fundamental to the resulting outcome and interpretation of the network (Butts 2009). Fortunately, when reconstructing a transport network the nodes can be quite easily thought of: they are the places where transport starts, converges, transforms and/or ends. The choice of arches is rather more difficult: it can represent the movement of one or more persons, of goods, or of information. This list is not exhaustive, and must be critically addressed in the reconstruction of transport networks.

A good overview for different reconstruction techniques applicable specifically to transport networks, although this example entails 'exchange' networks – the principle is similar, is presented by Rivers *et al.* (2013). A critical comment is that none of the presented approaches take particular account of the natural environment. One way to account for this is to use cost-based path-finding tools, examples of which are Bell *et al.* (2002) for land-based transport or Slayton (2018) for maritime transport. So far the inclusion of the natural environment in the construction of transport networks is not yet fully explored, although gravity networks as presented by Knappett *et al.* (2008) certainly provide the necessary framework. Another challenge would be to construct a network that is not static but both spatially as well as temporally dynamic, responding to external changes such as demography or economic relations, something which so far has not really been explored.

Different types of networks can arise from the above procedures. The simplest form is a random network, where nodes are randomly connected. Many networks were found to be non-random, however, formed through growth and preferential attachment, so that the degree distribution (the fraction of nodes in a network with a certain number of links) is not normally distributed but rather follows a power law. This type of network is known as scale-free (Barabási and Albert 1999; Barabási 2009). The majority of nodes will have less than average connections, while a small number of nodes will have an above average number of connections. Another type of network is known as 'small-world', which explains the real-world phenomenon that a lot of networks are not completely ordered, but also not completely random. In the region between these two there are networks that are highly clustered, while the average path length is as small as possible (Watts and Strogatz 1998). One recognised problem in archaeology is that actors in the network are often only aware of their own cluster, and although they cooperate in long-distance networks they are often not aware of this (Brughmans 2013b, 643). These two networks are the most commonly recognised in archaeological research, although the most difficult step is to explain why these types of networks arise (Brughmans 2013b, 648).

Network analysis is often seen as a next step in a network approach to archaeological problems, although a quantitative approach is not necessarily pivotal (see for example Sindbæk 2007). Popular quantitative methods are measures of closeness and betweenness centrality, such as used by Isaksen (2008) in his analysis of the Antonine Itinerary and the Ravenna Cosmography. Closeness centrality in this respect means the ease by which a node can be reached by any other node. Betweenness centrality is the chance that a node will be passed through by a shortest route between two other nodes. Both can be useful, as they can (with some critical consideration of the choice of nodes/arches or completeness of archaeological data) be related to the function of the node in an archaeological network, such as a central place or gateway site. Graham (2006) also investigated the Antonine Itinerary, but used path length to compare the homogeneity between regions, arguing that shorter path lengths indicate that a region is more likely to be culturally homogeneous. Furthermore, he compared network cohesion between regions, where the cohesion measure represents how close a network is to being a fully connected network (i.e. all nodes are connected to all other nodes). Finally Graham addressed network fragmentation, which investigates the vulnerability of the network to the removal of the most important node (and subsequently the second-most important node, etc.). Brughmans (2010) is aware of the incomplete adoption of network analysis techniques in archaeology, and addresses some other (perhaps less common) techniques such as m-slices, degree measure and domain measure. He is critical of the limited methodological scope of network analysis in archaeological research, and emphasises that archaeological reasoning and questions should be the driving factor from the outset before adopting a network approach and specific methodologies, rather than developing a standardised package of network analysis techniques (Brughmans 2013b, 654–655). A more in-depth overview of network science and formal network analysis techniques relevant to this study is provided in sections 1.4.6.5-1.4.6.6.

1.4.6 Computational archaeology

Computational archaeology is an umbrella term for computer-based analytical approaches in archaeology. This section will deal with the aspects often involving computational archaeology that were discussed earlier, including GIS (section 1.4.6.1) least-cost path analysis (sections 1.4.6.2-1.4.6.4), networks and network analysis (sections 1.4.6.5-1.4.6.6) and agent-based modelling (section 1.4.6.7).

1.4.6.1 Geographic Information Systems

A Geographical Information System (GIS) in its essence is a tool to store, retrieve, manage, analyse and visualise spatial data. As a concept, GIS is also concerned with the description, prediction and explanation of spatial patterns and processes (Longley 2005, xi). This approach regards GIS as a separate science of spatial data with its own research issues, an approach that has also been adopted terminologically by some researchers as Geographic Information Science (GISc or GI Science) (Wright *et al.* 1997; Goodchild 2010).

The breakthrough of GIS in archaeology is commonly accepted to be the publication of Allen *et al.* (1990). It gained some popularity due to the ability to easily communicate its methods and results as well as simple, understandable and convincing visualisation (Verhagen 2007, 16). However, voices were also raised regarding the uncritical adoption of new GIS methods purely because the computational power of GIS allowed it, the reduction of archaeological GIS to the production of pretty pictures and the (environmentally) deterministic nature of most research (Wansleeben and Verhart 1997). However, taking into account this critique and setting relevant archaeological research questions as the driving factor behind choosing methodologies rather than the other way around has largely resolved this issue.

1.4.6.2 Least-cost path analysis

The principles of least-cost paths have been around for quite some time outside archaeology, with first applications being developed in the late 1950s and over 200 algorithms already known by the 1970s (Deo and Pang 1984). The essence has remained the same: a least-cost path (LCP) is the cheapest route from a source to a destination over a surface of a pre-defined cost (Fig. 1.7). The costs can represent virtually anything, but most archaeological case studies have used either energy expenditure or time expenditure of walking to model routes. The implicit assumptions herein is thus that people always try to optimise (or 'economise'; Surface-Evans and White 2012, 2) the costs they spend travelling, which may be true for frequently used routes but less so for incidental journeys. In archaeological case studies so far, a choice between cost currencies is often made implicitly without discussing the underlying reasoning (Herzog 2014a, 233).

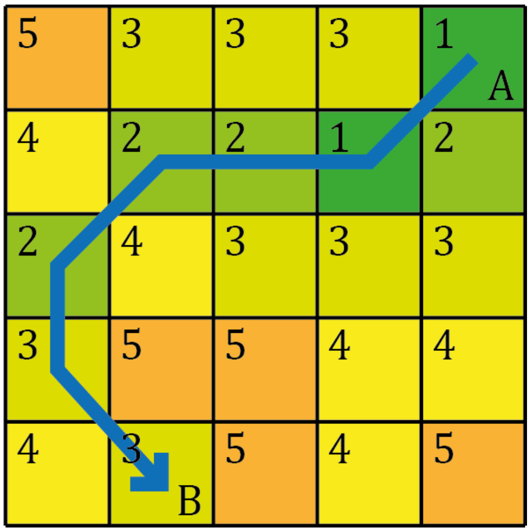


Figure 1.7. The route from A to B follows the 'cheapest' path over the raster, with the values in the raster representing the costs of movement.

Most, if not all, implementations of LCP analysis are a multi-step procedure. First, a raster surface has to be created of the costs that it takes to travel over a cell, after which the accumulated costs radiating outwards from the source are calculated over this cost surface, and finally the path from the destination is calculated by 'descending' down the accumulated cost surface back to the source.

1.4.6.3 Establishing the costs of movement for least-cost path analysis

In the process of generating LCPs the choice of costs to include in the cost surface is the first and arguably most important choice, as it has the greatest impacts on the resulting output. A majority of archaeological case studies use slope, the derivative of elevation, as the main component for calculating costs (e.g. Bell and Lock 2000; Llobera 2000; Fábrega-Álvarez and Parcero-Oubiña 2007; Zakšek *et al.* 2008). This is understandable, since in many areas of the world most variation in time or energy expenditure is the result of moving up or down sloped terrains. However, it comes with a number of difficulties, the foremost being the anisotropic nature of slope as a cost component (i.e. it makes a big difference whether one is moving perpendicular or parallel to the direction of slope). This aspect has been at the centre of a number of archaeological studies, and a valuable treatment is provided by Herzog (2013c). Various functions have been developed to calculate slope-based costs in units of either energy or time, primarily centred around hiking (e.g. Naismith 1892; Pandolf *et al.* 1977; Ericson and Goldstein 1980; Langmuir 1984; Tobler 1993; Minetti *et al.* 2002; Llobera and Sluckin 2007) but incidentally also around wheeled transport (Llobera and Sluckin 2007). A comparison and evaluation of slope-based cost functions for walking is made by Herzog (2013d). Furthermore, for wheeled transport Raepsaet (2002, 24) provides a function for the calculation of required traction force given the weight of the pulled load, the slope and the paving of the surface.

Of course there are other aspects that can impact the costs of potential routes, examples being vegetation and soil properties, or other more or less tangible aspects such as visibility, field of view, presence of waymarkers, territories and areas of social attraction/repulsion. While the most realistic route may perhaps be achieved by including all possible factors influencing movement, many of the cost components are either entirely unknown to us or require a substantial amount of assumptions, and in most cases the relative importance of and interaction between cost components is unknown. It has been argued that in an attempt to approximate past reality, a model with only reliable cost components is a good starting point that can be refined further when more information becomes known or particular archaeological hypotheses need to be tested (Batten 2007, 153–54; Herzog 2014b, 5), and that line of thought will be followed here as well.

The specific topography of the Netherlands, and particularly that of the Rhine-Meuse delta that covers the largest part of our research area, makes a slope-based cost surface construction not very appropriate. The majority of the Dutch river area is flat and only sloping very gently from east to west following the Rhine-Meuse delta, while the elevation differences around the edges of the research area, on the transitions to the Pleistocene sandy landscapes, only very rarely exceed some tens of metres. On top of that the Dutch landscape has undergone significant natural and anthropogenic changes since the Roman period. A slope-based model based on modern elevation data, as is often used in areas of greater and more stable relief, would thus not be suitable or meaningful at all. A further complication is the specific character of a delta landscape, with multiple channels that form barriers (and sometimes conduits) for movement.

In the Dutch river area, the variety in effort that one needs to move over the terrain itself is more important than relief. It can possibly be broken down into a number of individual components such as vegetation, soil properties (e.g. lithology, structure), soil type, and hydrology, although it would be very difficult to assess the impact of each one independently and they may also be dynamic due to aspects such as seasonality. Some studies have aimed to include terrain factors in their cost calculations or even exclusively used it as a cost component (e.g. Bell *et al.* 2002; Fiz and Orengo 2008; Verhagen 2013), and one study has found terrain to sometimes be a more important limiting factor than slope (De Gruchy *et al.* 2017) in cost distance calculations. In contrast to the more commonly used slope-based costs, only very little research is done on the effects of terrain on movement costs. In fact, only one hiking cost function is available that readily includes a terrain coefficient, as well as the effect of carried loads while hiking (Pandolf *et al.* 1976; 1977), with the terrain coefficients given by Soule and Goldman (1972). De Gruchy *et al.* (2017) argue that these terrain coefficients are mostly appropriate for energy-based cost functions, and propose some new coefficients that are better suited for time-based cost functions.

An additional complication is introduced when including water-based transportation in addition to land-based transportation modes. Streams and rivers can function as impassable barriers or areas of relatively high costs to traverse when only considering land-based transport modes, but when water-based transport modes are available to a traveller they suddenly become a conduit, and importantly, one with anisotropic costs and likely some form of access costs. Multimodal forms of modelling movement have been experimented with to some degree (e.g. Howey 2007; Bevan 2011; Livingood 2012), and an approach that could be comparable to the situation of the Dutch river area was developed by Wheatley and Gillings (2002, 156–57), who model waterways as low-cost corridors of movement that are only accessible after overcoming a small barrier of high cost that represents the transfer between modes.

1.4.6.4 Implementation of least-cost path analysis in GIS software

All commonly used GIS packages have an implementation of LCP analysis available, although the realisation and actual outputs differs between all and it is mostly not visible to the user what the root of these differences is, meaning that results in one software package are not easily reproducible in others (Gietl *et al.* 2008). The algorithms in most software packages are based on one published by Dijkstra (1959; cf. Cormen *et al.* 2001, 595–99; Herzog 2013c, 185), which was originally constructed to calculate shortest paths in a graph but is implemented in GIS on a raster basis, wherein the centres of the raster cells represent the nodes and links are formed between neighbouring cells. One of the shortcomings of most implementations is that only so-called Queen's moves are taken into account (i.e. the eight cells that neighbour a cell in horizontal, vertical and diagonal directions), which leads to elongation errors that can potentially increase the path length with respect to the true optimal path by up to 20% (Herzog and Posluschny 2011, 213–14; Herzog 2013c, 188–89). Such errors can be reduced by introducing larger neighbourhoods through allowing Knight's moves or even more complex ones, although this becomes very computationally intensive on larger scales (Herzog 2014b, 3) and is not a standard part of most GIS implementations of the Dijkstra algorithm.

Other algorithms have been developed as well (see Festa 2006), such as the A* algorithm (Hart *et al.* 1968), which is a modification of the Dijkstra algorithm to compute paths more efficiently, and the algorithm of Collischonn and Pilar (2000) that is proposed by Gietl *et al.* (2008) to better model paths in mountainous areas, although so far these have not been commonly implemented in GIS packages.

The procedures a user has to undertake to generate a LCP within the GIS software are comparable, although terminology may differ between packages. The common commercial package ArcGIS (Desktop version 10.1-10.3; Pro version 2.0) by ESRI has been used for GIS-related analysis in this research, and this introduction will therefore follow the procedures and terminology in that package. Firstly, an accumulated cost surface for one point must be created from the cost raster. For isotropic costs (i.e. costs that are independent of the direction of movement, such as terrain), the Cost Distance procedure is used, while for anisotropic costs (e.g. slope), the Path Distance procedure is available. For the latter, this study makes use of the option to include a vertical raster to represent water-based transport. The vertical raster contains (artificial) elevation values that are used in the Path Distance procedure to calculate the slope over an elevation when moving from one cell to its neighbour. This can be exploited for instance to represent downstream movement through a negative slope and upstream movement through a positive slope. Through a conversion table, the slope values are then transformed into vertical factors, that are used as a multiplier to the regular costs of movement that are derived from the cost raster. Modelling water-based movement through this method is explained in more detail in section 5.2.4.

Both the Cost Distance and the Path Distance procedures produce two raster outputs, namely the accumulated cost surface, wherein the value of each raster cell is the cost it takes to reach that cell from the source, and the cost backlink, wherein the cells contain the direction that one needs to move over the accumulated cost surface to return to the source. The cost backlink is an important component, as some LCP implementations instead use a hydrological drainage algorithm to simulate the generation of the optimal LCP, which has shown to not always produce the same results, regardless of the use of Dijkstra's algorithm to produce the accumulated cost surface (Herzog 2013c, 186).

The final step is to calculate the path from a destination to the source. This makes use of the Cost Path procedure, regardless of whether the accumulated cost surface is isotropic or anisotropic. As input it requires the accumulated cost surface as well as the cost backlink, for the reason stated above. The output is a raster that highlights the cells that are part of the LCP, which can subsequently be used for further analysis, for example by converting it into a vector format (using the Raster to Polyline procedure) which provides additional analysis options. Optionally, the Cost Path procedure can trace LCPs to the source from multiple destinations simultaneously, although since the output remains a single raster, it becomes more difficult to analyse LCPs individually.

1.4.6.5 Networks

Networks have become a common concept in archaeology and particularly the use of network science in computational archaeology has grown substantially over the past decade (Brughmans 2013a, 549; Collar *et al.* 2015, 2). Network science has been defined as the study of the collection, management, analysis, interpretation and presentation of relational data (Brandes *et al.* 2013, 2). Although for many network researchers the term may imply a formal and explicit structure of entities that are connected to each other on the basis of some relation that the entities have, it has also been applied more loosely in archaeological and historical research to discuss interactions between people in the past, sometimes concurrent with the concept of 'connectivity'. Examples are Horden and Purcell (2000) and Malkin (2011), who adopt concepts from the vocabulary of network science to explain archaeological and historical phenomena that may be captured in networks without expressing them in a quantitative way, arguably because there is not enough data to quantitatively study such phenomena with statistical significance (Malkin 2011, 19, 25).

Researchers in network science argue that the greatest innovation in the introduction of network science lies in the potential to place relationships at the heart of analytical methods; it is an approach to how and why relationships matter (Collar *et al.* 2015, 6). Collar *et al.* (2015, 10; see also Knappett 2013a, 4–5) argue that despite being similar to lines of research commonly attributed to the processual school of archaeology, network science with its relationship approach also fits in with post-processual thinking, by linking interaction between peoples with the interaction of people with their material, and possibly even between materials themselves.

An abstraction of interaction into **networks** is aided by the ease in which the archaeological record can be expressed as so-called nodes. **Nodes** are the discrete entities that form the vertices of the network, and can range in size from e.g. individual objects and assemblages to archaeological sites and regions, depending on the archaeological reality it aims to represent. The **edges** (or **links**) in the network that connect any pair of nodes are the representation of the interaction or relation that those nodes have, such as a potential transport route as the connection between two settlements. Edges can both be **directed** and **undirected**, the former meaning that the edge can only be travelled in one direction (e.g. from node A to node B) while the latter can be travelled in both directions. The term 'network' just refers to a set of nodes and edges, and this means that the network is not necessarily fully connected, i.e. all nodes do not have to be able to reach all other nodes. A network can thus potentially consist of multiple so-called **components** that are not connected to each other, and can even contain **isolated nodes** that are not connected to any other node.

As can be deduced, multiple distinct sets of network data may be conceptualised from an archaeological dataset or phenomenon, all depending on the (archaeological) problems that are addressed (Collar *et al.* 2015, 16). Similarly, what can be learned from such networks that are abstracted from the archaeological dataset is dependent on the questions that are being asked of those networks, for instance through the application of formal network analysis techniques.

Formal network analysis techniques have become more commonplace in archaeology, particularly influenced by social network analysis (Freeman 2004) through New Geography, and studies in social physics (Watts and Strogatz 1998; Barabási and Albert 1999). It would be far too extensive to go into detail as to the origins of these schools, their role in archaeology and the involved challenges of the cross-disciplinary application of techniques, topics extensively covered in studies such as Brughmans (2010; 2013a; 2013b; 2014), Knappett (2013b) and Collar *et al.* (2015), the latter providing a useful dictionary for common terms in network approaches in archaeology. Most notably, a challenge in the application of formal network analysis that became prominent in recent years is that they cannot be applied indiscriminately but must be steered by and tailored to the archaeological questions that are addressed (e.g. Brughmans 2013b, 654–55). This will be the outset of each of the studies presented in Chapter 6 (section 6.4 and onwards), using concepts of network analysis presented in the next section.

1.4.6.6 Network analysis

This section is solely dedicated to explaining the concepts borrowed from formal network analysis that this research utilises. It leans on the dictionary published by Collar *et al.* (2015) and the standard work of Wasserman and Faust (1994) which forms the basis of the aforementioned dictionary, as well as the documentation of Cytoscape (Shannon *et al.* 2003; Smoot *et al.* 2011), one of the mainstream software packages available for visualising networks and applying network analysis techniques through its Network Analyzer plugin (Assenov *et al.* 2008; Doncheva *et al.* 2012).

As has been mentioned in the previous section, a network consists of nodes and edges (or links). The nodes are the vertices of the network representing some discrete entities, and the edges represent the interaction between those entities. A number of network analytical procedures may be applied, which can be measured on individual nodes and edges in the network as well as for the network as a whole. The ones that are treated here are a mere subset of what is available, but they are selected on the basis of their appearance in Chapter 6.

The **shortest path length** is a relatively simple network measure, and lies at the basis of many of the other measures commonly performed under network analysis. It is defined as the length of the shortest possible path from node v to node s, written as $L(v, s)$.

Shortest path length can be weighted or unweighted, the former giving each traversed edge a value of 1, whereas the latter utilises some attribute given to an edge, such as travel time or geographic distance. Path lengths can also be computed for all paths to a single node, as well as for all paths in the entire network, which both can be quite ambiguously termed as **average shortest path length** or **average path length**. For a single node it is sometimes called ‘single source’ path length, such as in Python’s NetworkX library (Hagberg *et al.* 2008). The measure on a single node is simply the average of the shortest paths from that node to all other nodes (n; Eq. 1.1).

$$APL(v) = \frac{\sum_{s \neq v} L(v, s)}{n - 1} \tag{1.1}$$

The average for the entire network is the average of those for all single nodes, which can be calculated by summing all average paths lengths and dividing that by the number of nodes. From the former formula it can be deduced that this is also equal to the sum of all shortest path lengths divided by the number of combinations of nodes (equal to $n(n-1)$) including repetitions, which can be used for both directed (i.e. $L(v,s) \neq L(s,v)$) and undirected networks (i.e. $L(v,s) = L(s,v)$; Eq. 1.2).

$$\overline{APL} = \frac{\sum_v APL(v)}{n} = \frac{\sum_v \sum_{s \neq v} L(v,s)}{n(n-1)} \tag{1.2}$$

For undirected networks only it is also equal to the sum of shortest path lengths without repetitions divided by the number of unique pairs of nodes (equal to $n(n-1)/2$). The primary advantage of this formula is a shorter computation time as only half the amount of shortest path lengths needs to be calculated (Eq. 1.3).

$$\overline{APL} = \frac{2 \times \sum_v \sum_{s > v} L(v,s)}{n(n-1)} \tag{1.3}$$

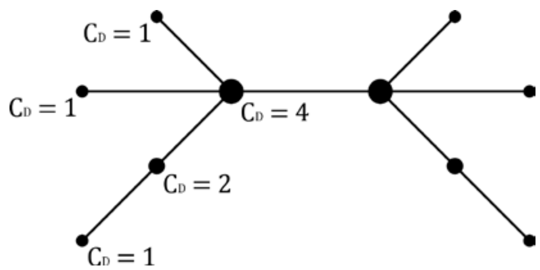


Figure 1.8. Schematic example of degree centrality. The central nodes have 4 neighbours, the peripheral nodes only 1.

Some of the most commonly applied measures in network analysis are so-called centrality measures, which aim to give some sense as to how central a node is in the network in relation to other nodes. The simplest of such measures is **degree centrality**, or sometimes simply degree (Fig. 1.8), which is a measure of the number of edges that join a node. In the case when self-loops are excluded, it can also simply be called **number of neighbours**. In this sense a node is considered central when it is has a large number of edges to other nodes. In directed networks degree can be specified in an in-degree and out-degree, which are respectively the number of edges that go towards a node and the number of edges that depart from it. Shaw (1954) was among the first to pose degree as a centrality index, but according to Freeman (1979, 220) it was most simply and proficiently formalised firstly by Nieminen (1974; Eq. 1.4).

$$C_D = \sum_s a(s,v) \tag{1.4}$$

In Equation 1.4 C_D is the degree centrality of node v, calculated as the sum of the evaluation $a(s,v)$ for all possible nodes s, where $a = 1$ if a node s shares an edge with node v, and $a = 0$ when there is no direct edge. Degree can also be used as a property to characterise the entire graph, in which case it is termed average degree. It is simply calculated by dividing the sum of all degree centrality values by the number of nodes (n; Eq. 1.5).

$$\overline{C_D} = \frac{\sum_v C_D(v)}{n} \quad (1.5)$$

Degree centrality values are dependent on the number of nodes present in the network, and can be normalised by dividing it by the maximum possible degree, which is equal to the total number of nodes minus 1, resulting in a measure called **network density** (Eq. 1.6).

$$C_{D\,normalised}(v) = \frac{\sum_s a(s,v)}{n-1} \quad (1.6)$$

Betweenness centrality (Fig. 1.9) is another measure of centrality, and put simply, it calculates for a node the number of shortest paths between any pair of other nodes that pass through that node, as a fraction of the total amount of node pairs in the network excluding that node. In an undirected network that total amount of node pairs is equal to $(n-1)(n-2)/2$, where n is the total number of nodes. In more tangible terms, betweenness centrality may be seen as the amount of control a node has over flows in the network, to the point that nodes with high betweenness centrality have the potential to disconnect parts of the network when they are removed. The idea of such a centrality was first posed by Bavelas (1948) and more formalised by Freeman (1977; Eq. 1.7).

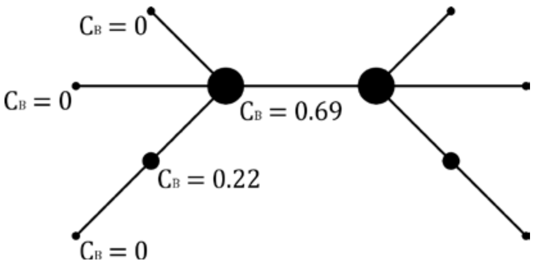


Figure 1.9. Schematic example of betweenness centrality. The central nodes have a high betweenness centrality because they are on all paths between the left-hand and right-hand side of the network. The peripheral nodes have a betweenness centrality of 0 because no paths go through them.

$$C_B(v) = \sum_{s \neq v \neq t} \frac{p_{st}(v)}{p_{st}} \quad (1.7)$$

In Equation 1.7 C_B is the betweenness centrality of node v, which is calculated by finding for each possible pair of nodes s and t the amount of shortest paths between them that pass through v ($p(v)$), divided by the total amount of shortest paths between s and t (p_{st}). Current software implementations, for instance Cytoscape and NetLogo's network extension, use the algorithm published by Brandes (2001). The C_B in this formula is a non-normalised value that is dependent on the size of the network, and for this reason it is commonly normalised by dividing it by $(n-1)(n-2)/2$ to arrive at values between 0 and 1 (Eq. 1.8).

$$C_{B\,normalised}(v) = \frac{2 \times \sum_{s \neq v \neq t} \frac{p_{st}(v)}{p_{st}}}{(n-1)(n-2)} \quad (1.8)$$

Closeness centrality (Fig. 1.10) is another measure of centrality, and it is founded on the principle that a node is most central when the average distance to reach all other nodes in the network is minimal. In that sense it is the reciprocal of the farness, i.e. how far a node is from all other nodes. Such forms of centrality were explored by Bavelas (1950) and a frequently cited formalisation is by Sabidussi (1966; Eq. 1.9).

$$C_C(v) = \frac{1}{\sum_{s \neq v} \rho(s, v)} \tag{1.9}$$

In Equation 1.9 C_C is the closeness centrality of node v, which is calculated by taking the sum of the distances ρ between node v and all possible nodes s (essentially the farness), and dividing 1 by that number to arrive at closeness. Similar to betweenness centrality it is dependent on the size of the network, and is therefore commonly normalised by multiplying it by the total number of other nodes (Eq. 1.10).

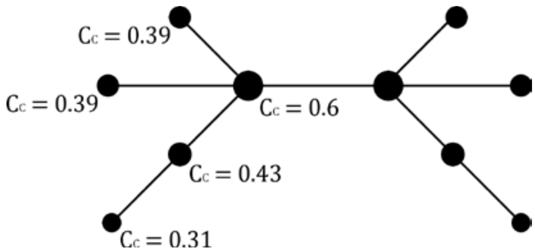


Figure 1.10. Schematic example of closeness centrality. The central nodes have a higher closeness centrality than the peripheral nodes because they are easier to reach from all other nodes.

$$C_{C\ normalised}(v) = \frac{n - 1}{\sum_{s \neq v} \rho(s, v)} \tag{1.10}$$

A different kind of network measure applied on individual nodes is the **clustering coefficient** (Fig. 1.11). It is a measure of the extent to which the neighbours of a node are also neighbours to each other. It was popularised in the research by Watts and Strogatz (1998) on so-called 'small-world' networks. For undirected networks it is calculated for a node v with its k_v number of neighbours by dividing the number of edges that exist between its neighbours (e_v) and the maximum number of edges between those neighbours ($kv(kv - 1)/2$; Eq. 1.11).

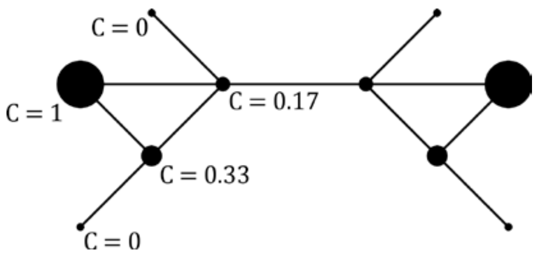


Figure 1.11. Schematic example of the clustering coefficient. The left- and right-most nodes have a clustering coefficient of 1 because both their neighbours are also neighbours to each other. The central nodes have more neighbours, but since they are almost not connected to each other the clustering coefficient is relatively low.

$$C(v) = \frac{2 \times e_v}{k_v(k_v - 1)} \tag{1.11}$$

Clustering coefficients are also often computed as a measure for the entire network, resulting the average clustering coefficient, which was used by Watts and Strogatz (1998) to determine when a network can be considered a 'small-world' network (Eq. 1.12).

$$\bar{C} = \frac{\sum_v C(v)}{n} \tag{1.12}$$

There are some network measures that are solely intended to describe the character of the network as a whole. **Network heterogeneity** is one such measure, and it represents the tendency of a network to form so-called hub nodes that command a large number of edges, among a larger number of less-connected nodes. It was developed to bridge the gap between ideal star-shaped networks that have a single node with high centrality values (e.g. degree) with large networks that have only vaguely defined centres often consisting of more than one node (Snijders 1981, 164). There are various definitions on how to scale the variance in the degree centrality of nodes to arrive at network heterogeneity, but its application in this study follows the formalisation of Dong and Horvath (2007) which was also implemented in Cytoscape. It calculates heterogeneity by dividing the root of the variance (essentially the standard deviation) of the degree centrality by the average degree (Eq. 1.13).

$$Heterogeneity = \frac{\sqrt{\sigma^2(C_D)}}{\overline{C_D}} \tag{1.13}$$

Network centralisation is a rather ambiguous term by being dependent on what is meant by centrality (e.g. degree, closeness), as noted by Freeman (1979, 226–27). What all variants of network centralisation have in common is that it is a measure of the extent to which the centrality of the most central node exceeds that of the other nodes. A network where nodes have a rather homogeneous centrality is thus expected to have a low centralisation. Freeman (1979) provides an overview of the calculations of network centralisation based on all three centrality measures mentioned earlier, but the one presented here is based on degree centrality, which is derived from the formalisation of Dong and Horvath (2007; which in itself is just a simple modification of Freeman 1979, 230) and is implemented in Cytoscape (Eq. 1.14).

$$Centralisation = \frac{n}{n-2}\left(\frac{\max(C_D) = \overline{C_D}}{n-1}\right) \tag{1.14}$$

1.4.6.7 Agent-based modelling

Agent-based modelling is a form of spatial dynamical modelling, which involves rule-based simulation models. As it can be both spatially as well as temporally explicit, it is especially suitable for exploring changes through space and time. Agent-based modelling combines ideas of chaos theory and the agency concept. Although not always utilising the term 'agents', Doran (2014) argues that the basic approaches were already present in early simulation modelling at least 40 years ago.

Chaos theory is rooted in complexity theory, and its basic concept is that small changes in initial conditions yield entirely different outcomes. Complexity theory is the study of complex systems, which investigates how interactions between parts of a system give rise to collective behaviours of a system and determines how it interacts with its environment. This ties in well with the agency concept, which is not always unambiguous in archaeology (cf. Dobres and Robb 2000, 3–4) but is usefully termed by Hodder as that directed and intentional behaviour of individuals leads to structural change, and thus societies are the result of non-static negotiations between changing and uncertain perspectives (Hodder 1987, 6).

Agent-based models are thus especially suitable to study cause-and-effect chains and to explore how macro-scale patterns (which are found in the tangible archaeological material) emerge from micro-scale actions (Railsback and Grimm 2012, 10). Notably, agent-based modelling might be argued to be one way to reconcile processual and post-processual approaches in archaeology (cf. Lake 2014, 268), as it builds a rule-based (logical) model of the economy or of spatial relations, yet emphasises the role of the decisions of the individual. Examples of successful applications of agent-based modelling in case-studies related to the current research are Kohler *et al.* (2005) on settlement pattern development in relation to environmental factors; Graham (2006) on information travel on networks; and Heckbert (2013) on an emergent trade network. Regional spatial economically explicit agent-based models have so far not really been developed, although the latter example and a recent project on the economy of an Iron Age hill site (Danielisová *et al.* 2015; Štekerová and Danielisová 2016) are certainly a step in that direction.

One final aspect that cannot be underestimated is the testability of a model. This does not only relate to agent-based modelling, but also to models of site location or networks. Whether through looking at archaeological evidence to test the model results or applying sensitivity analysis to test the robustness of the model, it is important to do so in order to increase a model's plausibility. As Bell (1994, 97) stated: "the degree to which a theory is testable is the most important single indicator of its potential to contribute to the advance of archaeological theory".

1.5 Outline of thesis structure

The aim of this chapter was to present a general background to the current research. The next chapter will deal with the construction of the first important building block for any further analysis, namely the physical palaeogeography. Firstly, the methodology of the reconstruction is presented, after which the general reconstruction is performed. The chapter ends with an analysis and discussion of the reconstruction of the physical palaeogeography. One of the important aspects herein is an appreciation of the uncertainty that is involved.

The third chapter presents the archaeological database, firstly through a presentation of the available datasets, a discussion of the used methodology for constructing the dataset and reinterpreting the related chronology. The fourth, fifth and sixth chapter will deal with the first part of the archaeological palaeogeography, namely transport and transport networks. In the fourth chapter the characteristics transport of transport in the Dutch *limes* area will first be detailed. The fifth chapter introduces the methods and presents the results of how transport connections can then be modelled. This will culminate in the sixth chapter in the construction of transport networks, and the analysis of these networks including some archaeological case studies of the Dutch *limes* area.

The seventh chapter deals with the other aspect of the archaeological palaeogeography, which is an analysis of settlement locations, including aspects from previous chapters such as the natural palaeogeography and transport networks, among other factors.

The eighth chapter summarises the results of this research, contextualises the most important conclusions and explains how these approaches in this study contribute to the advancement of the application of computational approaches in archaeology and to our understanding of the archaeology of the Dutch *limes* area.

2 Natural palaeogeography

In section 1.4 of the previous chapter an introduction into natural palaeogeography was provided, describing that it is rooted in a long tradition of the mapping of our physical environment. This chapter will present the work done on the natural palaeogeography of the Dutch part of the Roman Lower Rhine *limes* within the 'Finding the limits of the *limes*' research project.

2.1 Background

In order to provide a context for the rest of this chapter, this section will present a background to the methodologies and research frameworks used in physical palaeogeography in the past. In the introduction chapter some examples have been given of research done from roughly the 1950s until now. Many of these undertakings are limited in spatial extent, limited to certain landforms or depositional environments and perhaps excluding other contemporary landforms and depositional environments, or limited to specific timeframes. This is of course the result of the varying underlying research aims for which these maps were developed.

In early palaeogeographic research, the goal of the exercise was often not reconstructing the palaeogeography itself. Maps were constructed with varying aims, often to look into the genesis of certain landforms or regions during specific time periods, and occasionally in relation to archaeological excavations. Examples include, but are not limited to: Tuinstra (1951) on medieval northwest Noord-Brabant; Wiggers (1955) on the Noordoostpolder region; Pons (1957) on the eastern river area; Bennema and Pons (1957), Zagwijn (1971), Vos (1983) and Westerhoff *et al.* (1987) on the evolution of the "Oer-IJ" estuary (Noord-Holland); Ovaa (1958) on the Holocene developments of western Zeeuws-Vlaanderen; Pons and Wiggers (1959; 1960) on the Holocene genesis of Noord-Holland and the Zuiderzee region; De Smet (1960) on the Dollard-Eems estuary; Kwaad (1961) and Ente *et al.* (1975) on the geogenesis of northern Noord-Holland; Pons *et al.* (1963) and Beets *et al.* (1992) on the Holocene North Sea coast evolution; De Smet (1969) on the Hunze river in Groningen; Jelgersma *et al.* (1970) and Zagwijn (1984) on the coastal dunes in the western Netherlands; Ente (1971; 1976) on the Holocene Lake IJssel region; Ente (1973) on the IJssel delta; Pons and Van Oosten (1974) on the soils of Noord-Holland; Roeleveld (1974), Griede (1978) and Griede and Roeleveld (1982) on the coastal areas of Groningen and Friesland; Zonneveld (1978) and Van de Meene and Zagwijn (1979) on the Rhine course through Germany and the Netherlands during the Quaternary; Harbers and Mulder (1981) on the eastern river area during the Roman Period; Berendsen (1982) on the central river area south of Utrecht; Jelgersma (1983) on the Bergen inlet; and Hallewas (1984) on medieval Noord- and Zuid-Holland.

The first steps towards palaeogeography on a nation-wide scale were made by Pons *et al.* (1963), working on the coastal evolution through the Holocene. Zagwijn (1974) conducted the first holistic palaeogeographic approach on a national scale, not looking at isolated landforms or environments but rather at the natural landscape as a whole. This included two maps concerning the Holocene, depicting the physical geography around 7000 and 4300 years BP. Ten more palaeogeographic maps of the Holocene on smaller chronological intervals were published a decade later (Zagwijn 1986), also showing more spatial details. The maps were schematically constructed on a 1:500,000 scale, making them suitable for understanding long-term palaeogeographic developments. Following decades of new research and changing insights, De Mulder *et al.* (2003) published a new palaeogeographical map series. However, similar to the older maps, they were drawn more schematically to illustrate long-term regional and nation-wide developments in a larger context (Vos 2015, 5) and are thus not very useful for more detailed research on local to regional scales.

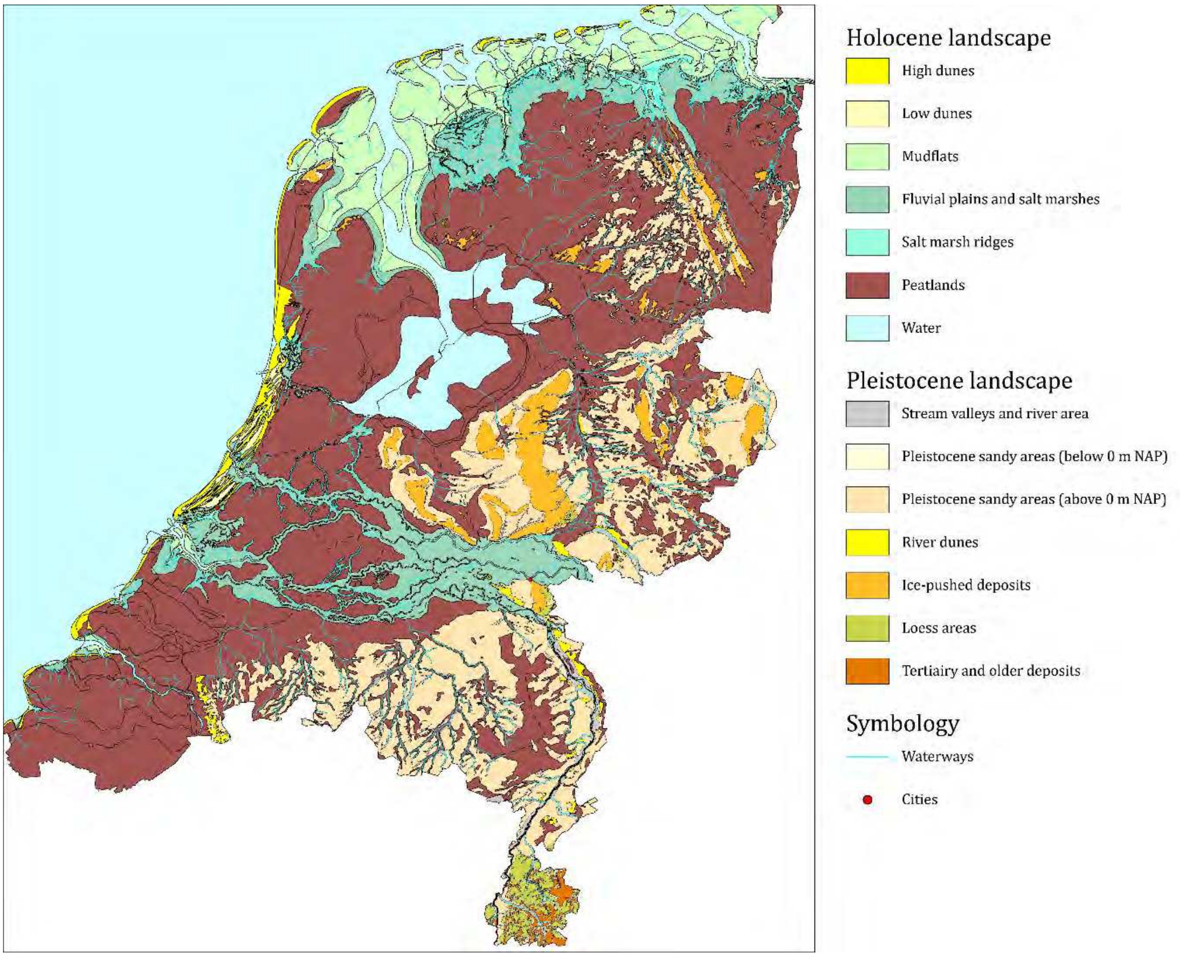


Figure 2.1. Palaeogeographic reconstruction of the Netherlands around AD 100 (from Vos and De Vries 2013).

A new palaeogeographic map series was developed by TNO[1] and RCE[2] in collaboration with the Dutch knowledge institute Deltares (Vos *et al.* 2011; Vos and De Vries 2013; Fig. 2.1). Part of this series has been published earlier in a preliminary form in '*De Steentijd van Nederland*' (Vos and Kiden 2005) and in the Dutch Archaeological Research Agenda (Vos 2006). The aim of this map series was to revise the map series by Zagwijn in more detail, based on recent insights and developments in geology, physical geography and related fields. Among the sources used are a number of recent regional palaeogeographic studies, some of which in turn are based on, or continuations of older palaeogeographic studies mentioned before. The more recent studies include Henderikx (1987) on the lower Rhine-Meuse delta; Pons (1992) on peat formation in the lower Netherlands; Vos (1992) on the Lauwersmeer region; Lenselink and Menke (1995) on the Lake IJssel region; Leenders (1996) on the peatlands of western North-Brabant; Vos and Van Heeringen (1997) on the south-western Netherlands; Fokkens (1998) on the western Frisian-Drentian plateau; Schoorl (1999) on the western Wadden region; Beets and Van der Spek (2000)

[1] *Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek* – Netherlands Organisation for Applied Scientific Research
[2] *Rijksdienst voor het Cultureel Erfgoed* – Cultural Heritage Agency of the Netherlands

on the North Sea coast; Berendsen and Stouthamer (2001), Cohen *et al.* (2012; 2014) on the Rhine-Meuse delta; Bazelmans *et al.* (2002) on the western Netherlands; Spek (2004) on the plaggen soils of Drenthe; Vos and Soonius (2004) on the Oer-IJ region; Vos and Gerrets (2005) on the Westergo region; Vos and Knol (2005) on the *wierden* area in the northern Netherlands; and Cohen *et al.* (2009) on the eastern Rhine-Meuse and IJssel area. Especially many of the more recent regional studies have been developed with an archaeological purpose in mind and map the entire palaeogeography rather than specific landforms, making them very suitable for incorporation into future archaeology-oriented palaeogeographic studies.

With the digitalisation of many sources such as the 1:50,000 geomorphological maps (Alterra 2008), the 1:50,000 soil maps (Alterra 2006), the digital height model AHN[3] (Rijkswaterstaat-AGI 2013) and data archives such as the coring database DINOloket of TNO[4] and the archaeological database ARCHIS of RCE[5], palaeogeographic mapping possibilities have been substantially improved. A palaeogeographic reconstruction of the Lower Rhine delta area between Vechten and Katwijk during the first two centuries AD was made as part of the project "A sustainable frontier? The establishment of the Roman frontier in the Rhine delta", through the combination and comparison of all aforementioned sources in a GIS (Van Dinter 2013). Although the scale is still set at 1:50,000 (limited by the scale of the sources used), the direct application of GIS allows for the mapping to be done in a much less schematic way, permitting a more differentiated subdivision compared to earlier palaeogeographic reconstructions performed over such large areas. A further benefit of the application of GIS is the possibility to use these palaeogeographic maps for further (qualitative and quantitative) analysis, as has been demonstrated for the location of military structures (Van Dinter 2013, 20–26) and for the carrying capacity of the landscape (Kooistra *et al.* 2013; Van Dinter *et al.* 2014).

Another recent project carried out at Utrecht University, bearing the title "The Dark Age of the Lowlands in an interdisciplinary light: people, landscape and climate in the Netherlands between AD 300 and 1000", aims to improve the understanding of the relation between climate and landscape changes and cultural adaptation and migration in the Dark Ages. Part of this project focussed on the dynamic landscapes in the Netherlands during the Late Holocene, and the relative importance of climatic, environmental and anthropogenic factors in landscape evolution. One of the goals was to produce a detailed reconstruction of landscape evolution in the coastal area, the river area and the sandy areas during the Late Roman Period and Early Middle Ages (Jansma *et al.* 2014a, 474) using a GIS-based methodology that involves documenting all landforms with their ages in a database to create time slice maps 'on the fly', largely based on the methodology previously designed for channel belt palaeogeography (Cohen and Stouthamer 2012). This project produced multiple dissertations, with the natural palaeogeography and human-landscape interactions being the main topic of Pierik (2017).

2.2 Aims of this study

As has been presented in the preceding section, past approaches involving reconstructions of the natural palaeogeography were done for smaller areas with specific goals in mind, or are too large-scaled (i.e. nation-wide scales) to be useful for detailed quantitative analysis. Steps have been made in recent years through the work of Van Dinter (2013) and Pierik (2017), that have

[3] *Actueel Hoogtebestand Nederland* – Up-to-date Height Model of the Netherlands
[4] www.dinoloket.nl
[5] archis.cultureelerfgoed.nl

produced maps of large areas but on a detailed scale, making them suitable for further quantitative applications.

The 'Finding the limits of the *limes*' project aims to apply quantitative approaches to the entirety of the Dutch *limes* area. Existing palaeogeographic reconstructions that fully cover this area are limited to the ones developed at nation-wide scales, and are too coarse for the intended use in this project. What is therefore needed in this project is a new reconstruction of the natural palaeogeography of the research area during the Roman Period at a scale suitable for detailed quantitative analysis. Van Dinter (2013) constructed such a map for the Old Rhine area, the northwestern section of the Dutch part of the Roman *limes*, and therefore this work is used as starting point in the current study. The aim of this part of the research is therefore to construct a natural palaeogeographic map for the Dutch *limes* area in the Roman Period, as much as possible using the methodology of Van Dinter (2013) so that uniformity is maintained with the existing reconstruction of the Old Rhine area.

2.3 Methodology

As was stated in the previous section, the aim of this part of the research is to construct a natural palaeogeographic map for the Dutch *limes* area in the Roman Period, largely following the methodology of Van Dinter (2013). The chronology poses some problems, as the landscape changes through time. For this reason, the map is constructed to reflect the palaeogeographic situation during the Middle Roman Period (AD 70-270), and when another time period requires changes to the map an alternative scenario is provided.

The goal of the mapping procedure is to construct a dataset of palaeogeographic units that is relevant to its intended use in this research on the Dutch *limes* area. That means that units need to be distinguished when they are distinctive in their potential and their use for habitation, agriculture, wood exploitation and transport in the Roman Period. An example of such a distinction is that of the fluvial landscape (see for example Fig. 2.1) into natural levees and floodplains, which have very different suitabilities for the aforementioned practices.

In general terms the Dutch *limes* area can be subdivided into three regions, each having a distinctly different character and in one case also requiring a different mapping strategy. These differences will be elaborated upon in the following sections. The regions recognised will be defined here as the 'western river area, the 'central river area' and the 'eastern river area' (Fig. 2.2). This section will describe the sources and the methodology used to map each area, but first it will introduce the main tool used in palaeogeographic reconstruction, namely GIS.

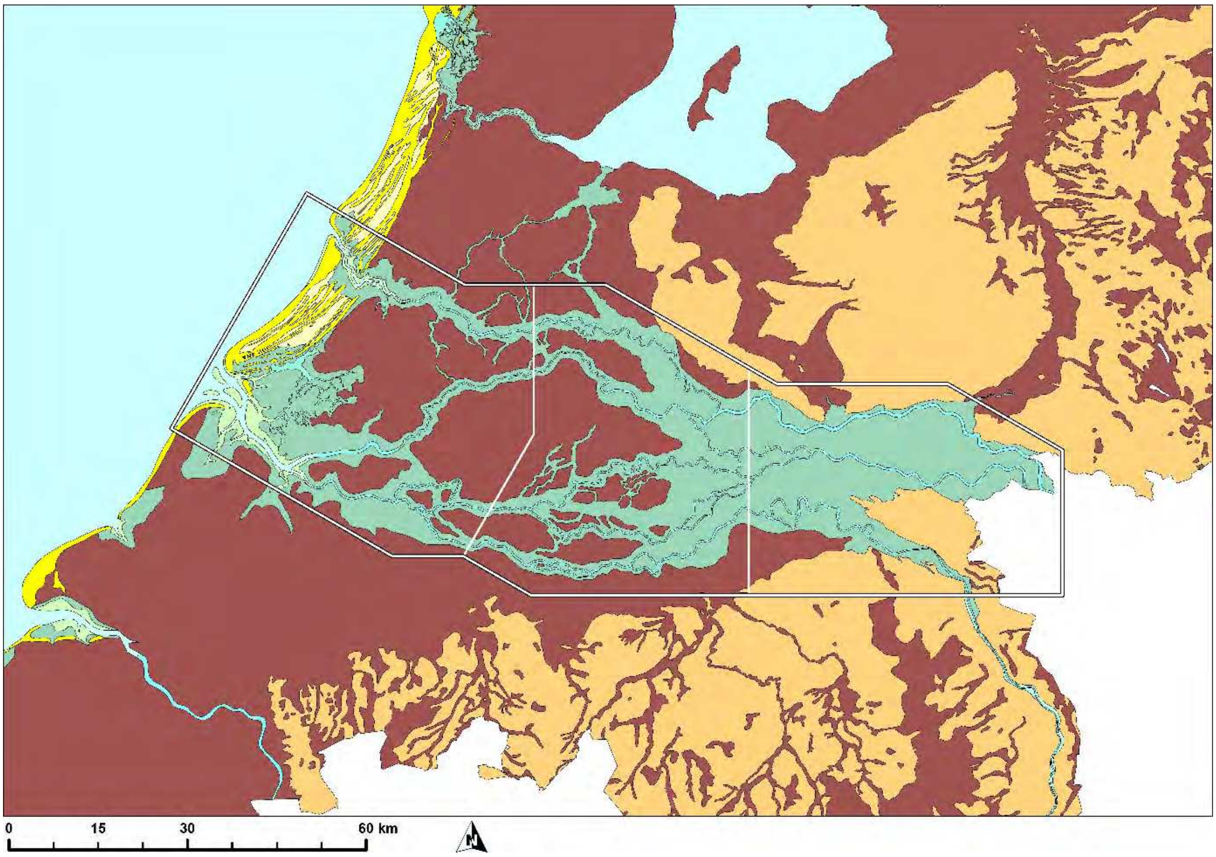


Figure 2.2 Outline of the research and subdivision into the 'western river area', 'central river area' and 'eastern river area', shown on the palaeogeographic map of the Netherlands around AD 100 (from Vos and De Vries 2013).

2.3.1 GIS and palaeogeographic reconstruction

Geographical Information Systems (GIS) have become very popular in archaeology since the 1990s as the prime tool for managing and analysing spatial information. Many software packages for GIS are now available, including some which are freely available such as GRASS GIS and QGIS. Popular commercial packages are MapInfo and ArcGIS. This research makes use of the ArcGIS software package, although it is certainly possible to use or develop similar methods and tools in other GIS applications.

For palaeogeographic research, GIS firstly serves as a tool for storing, retrieving and visualising spatial data. It allows for the quick projection of several map layers in a geographic space, in order to visually compare, detect and study spatial patterns. One example of such an application is the use of LIDAR-derived elevation data to investigate landforms recognised in other maps (Fig. 2.3). Secondly, GIS serves as a tool to create new spatial data, namely the palaeogeography of the Roman Period. This is achieved by overlaying the source map layers, and mapping palaeogeographic landforms recognised within them. For the western and central river area this is done manually (Fig. 2.4), while for the eastern river area an automated combination of datasets is applied. Details on the sources used in this study will be given in the next section, followed by a more elaborate description of the palaeogeographic mapping methodology.

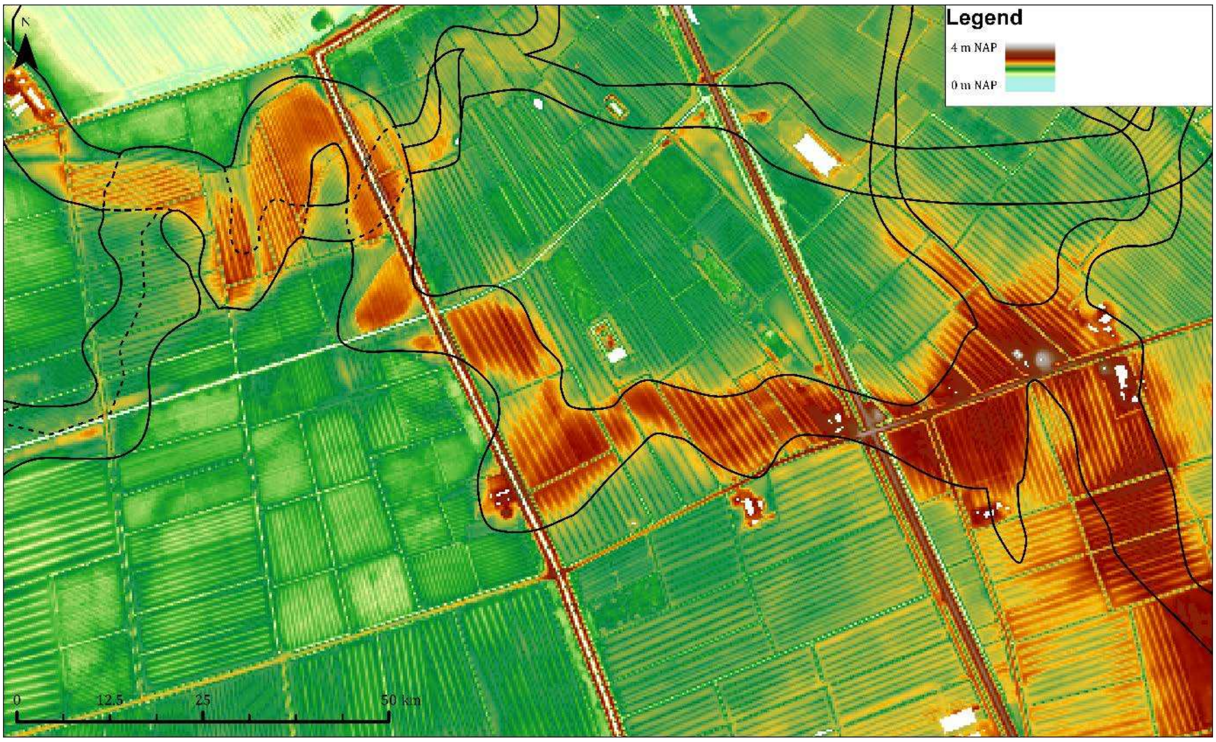


Figure 2.3. Example of a landform recognised on LIDAR-derived elevation data: the Schaik channel belt (cf. Cohen et al. *2012, ID 150) in the central river area.*

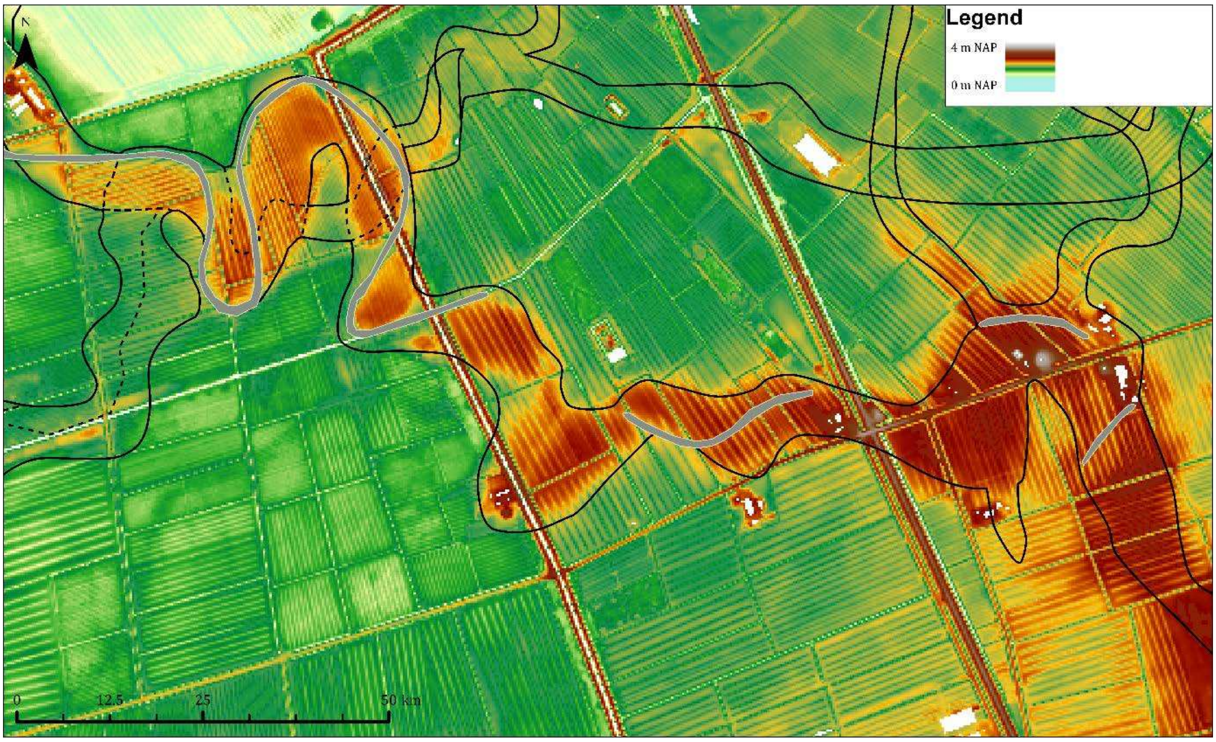


Figure 2.4. Example of the manual mapping of landforms in the palaeogeographic map: mapping the low-lying residual gully landforms of the Schaik channel belt using LIDAR-derived elevation data and channel belt data (Cohen et al., *ID 150).*

2.3.2 Sources

During the long tradition of mapping our physical environment, researchers and institutes in the Netherlands have produced a significant amount of datasets that can be used for palaeogeographic research. The sources most used in this study will be shortly described here.

2.3.2.1 Soil maps

In 1965, a soil map of the entire Netherlands was published at a scale of 1:200,000 (Stiboka[6] 1965). This map also included a geogenetic legend, with geomorphology and lithology as important elements (Berendsen 2007, 168). Soil maps were published at a scale of 1:50,000 between 1964 and 1995 by Stiboka based on a new classification method (De Bakker and Schelling 1966). This new legend was better aimed at the practical use of the soil map for agriculture, and included less geological information. For use in geological interpretations, this 1:50,000 map was less influential (Berendsen 2007, 168). More recently, the soil maps were released in a digital form on the same scale for use in GIS by the successor of Stiboka, Alterra (2006).

2.3.2.2 Geomorphological maps

The development of the current series of geomorphological maps at a scale of 1:50,000 was started in 1966 as a collaborative effort between Stiboka and the RGD[7]. A standard legend was developed based firstly on relief classes, distinguished using the angle of inclination and the length of the slopes, and then further subdivided into relief subclasses. Only after this first subdivision landform groups are distinguished, which are further subdivided into form units based on morphogenesis (Ten Cate 1983, 612). About 90% of the maps were finished by 1990 when government support was cut and the publication of new maps ceased (Van den Berg 2012, 173). In 1998 the mapping program was reinstated by Alterra using the newly introduced digital height model AHN, which increased mapping possibilities and production speed (Koomen and Maas 2004, 20). By 2003 the mapping program was finished and published in a digital form for use in GIS on a scale of 1:50,000 (Alterra 2008).

2.3.2.3 LIDAR elevation data

The digital height model AHN, created using light detection and ranging (LIDAR) has been under almost constant development since 1996. Rijkswaterstaat[8] together with the regional water boards ordered the development of an elevation map for the Netherlands, primarily to support water management. LIDAR, also known as laser altimetry, is an airborne remote sensing technique (Cracknell and Hayes 1991). The first generation of the AHN was completed in 2003, now known as AHN1 (Rijkswaterstaat-AGI 2005). The initial spatial resolution was limited to 1 measurement per 16 m^2. This gradually improved over the years along with the technological developments, so that the research area currently has 2 to 16 measurements per 16 m^2. At its highest resolution it is delivered as a 5×5 m grid, created using inverse squared distance weighting (ISDW). Using this interpolation technique means that some points outside the grid cell are taken into account as well, which tends to smooth the terrain, slightly decreasing the visibility of small-scale topography variations (Swart 2010; Van der Zon 2013). The AHN has a vertical resolution of 1 cm, although the vertical accuracy of each measurement point is much less. According to the specifications, the standard deviation due to stochastic laser measurement errors should be less

[6] *Stichting voor Bodemkartering* – Dutch Soil Survey
[7] *Rijks Geologische Dienst* – Dutch Geological Survey
[8] Directorate General for Public Works and Water Management

than 15 cm. Furthermore, systematic errors of approximately 5 cm can occur due to inaccuracies in flight path and vegetation effects, although corrections are applied when possible. In general, the precision of the data is improved by increasing the number of measurement points within a grid cell (Van Heerd *et al.* 2000; Brand *et al.* 2003; Berendsen and Volleberg 2007).

In order to improve the detail in the elevation model for the purpose of management of dikes and flood defences, data for the second generation AHN2 (Rijkswaterstaat-AGI 2013) was acquired between 2006 and 2012. This dataset has a spatial resolution of 8 to 20 points per m^2 (Swart 2010). At its highest resolution it is delivered as a 0.5×0.5 m grid. A grid cell value is determined only by the measurements available within the boundaries of the cell, which gives a more accurate description of the small-scale variations compared to AHN1 (Van der Zon 2013). However, the application of a newer version of the AHN also has some negative effects regarding its practical use in geomorphology, geology and/or archaeology, as more and more anthropogenic surface interference takes place in the current landscape (Berendsen and Volleberg 2007, 17). Meanwhile, the development of the third generation AHN3 already started in 2014 and is prospected to be finished in 2019.

2.3.2.4 Channel belt palaeogeography

The Rhine-Meuse delta in the Netherlands is characterised by a complex of sandy channel belts in a matrix of intercalated clay and peat. Throughout the Holocene, rivers have shifted their course due to lateral migration and meander cut-offs and even entirely changed course through avulsions (Allen 1965), with younger rivers partly eroding older channel belts (Berendsen and Stouthamer 2000, 315). This affects palaeogeographic reconstructions, as the river courses in the Roman Period were very different from those today (e.g. Berendsen 1990, although now partly outdated due to new insights).

The Rhine-Meuse delta has been studied intensively by researchers from Utrecht University, who created a large database of corings and ^{14}C-dates. A landmark work on the genesis of the landscape in the southern part of the province of Utrecht was published by Berendsen (1982). Since then, a number of PhD-theses and post-doc projects have increased the understanding of the delta (e.g. Törnqvist 1993; Weerts 1996; Makaske 1998; Stouthamer 2001), until the first palaeogeographic map series of the entire delta was published (Berendsen and Stouthamer 2000; 2001) at a 1:100,000 scale. Fieldwork and research continued with a number of new dissertations (Cohen 2003; Gouw 2007; Erkens 2009; Bos 2010; Van Asselen 2010; Toonen 2013), culminating in the publication of an updated channel belt palaeogeographic dataset (Cohen *et al.* 2012). This dataset has no fixed scale as it is mapped on the basis of the available data, which may vary in accuracy. The authors suggest that it is more accurate than both the 2001 publication (Berendsen and Stouthamer 2001) as well as 1:25,000 maps of the RGD of the 1980s and 1990s, based on the high coring density (typically >30 per km^2) and the use of LIDAR-derived elevation data to map channel belt boundaries (Cohen and Stouthamer 2012, 22).

2.3.2.5 Local data

Local data from geological or archaeological research was also used occasionally to clarify some uncertainties or add new local information. Such can often be the case in urban areas, where the previously mentioned sources have a low resolution or provide no information at all. Many archaeological reports of research conducted in the Netherlands are available in EDNA[9], an online archiving system set up by DANS and RCE.

2.3.3 Mapping the western and central river areas

For the western and central Dutch river area the methodology for mapping the natural palaeogeography is largely based on the approach developed by Van Dinter for the Old Rhine area in the Roman Period, in order to easily connect the new data to the substantial part that was already mapped in that study (Van Dinter 2013). The western and central river areas are characterised by the broad alluvial plain of the Rhine and Meuse, in which the rivers can migrate and in which avulsions can occur without majorly overwriting older deposits. It is for this reason that a lot of the older channel belts are preserved as recognisable elements in the landscape, allowing a mapping methodology with LIDAR elevation data in combination with other source data to map the Roman and pre-Roman channel belts in detail.

The methodology adopted from Van Dinter (2013) thus involves the manual combination of various source datasets in a GIS, which have already been introduced in the previous section. The geomorphological maps, soil maps and channel belt data form the starting point of the reconstruction, providing a general overview of the various landforms and their age. This image is subsequently refined using information from local (archaeological) research and LIDAR-derived elevation data. Particularly the distinction between fluvial landforms such as the stream ridges, natural levees, crevasses and floodplains can be made in this way, as LIDAR elevation data can be used both to add more spatial detail to the known fluvial landforms from channel belt data and geomorphological maps, and to map landforms not yet recognised in these and other sources (Berendsen and Volleberg 2007; Van Dinter 2013, 14). Furthermore, the 'natural levees' and 'floodplains' palaeogeographic units can be subdivided in relative elevation classes using the elevation data.

More detail on the mapping of the individual landscape units is provided in section 2.4.1. Limited by the source data, the palaeogeographic map has a scale of 1:50,000, although in practice it can be more accurate when landforms could be mapped with LIDAR elevation data under conditions of little to no post-Roman disturbance. Unfortunately, the extent of post-Roman disturbances, both natural and anthropogenic, is quite large in the Netherlands. Examples are post-Roman drift sand activity, dune formation, fluvial activity, peat exploitation and reclamation, and urban developments. The aspects of uncertainty are discussed in more detail in section 2.5.

2.3.4 Mapping the eastern river area

In contrast to the western and central river areas, the eastern river area has a much narrower corridor in which the rivers can move, banded by Pleistocene sands both in the north and south. Because of this, many channel belts dating to the Roman Period or older are buried or eroded by post-Roman fluvial activity, essentially hiding it for detailed palaeogeographic mapping using LIDAR elevation data. The eastern river area thus requires a different mapping strategy.

To map the fluvial landforms, the Roman and pre-Roman channel belts were taken from the channel belt dataset (Cohen *et al.* 2012) and superimposed on natural levees and floodplains filtered from the geomorphological maps. The Pleistocene sands including coversands, the fluvial terraces and the peatlands (occurring locally in brook valleys) were similarly taken from the geomorphological maps. Remaining anthropogenic elements such as urban development, dikes

[9] *e-depot Nederlandse Archeologie* – electronic depot Dutch Archaeology; easy.dans.knaw.nl

and sand or clay extraction pits were manually replaced with the most likely palaeogeographic element.

Without the use of LIDAR elevation data no distinction could be made between the elevation categories of the natural levees and floodplains. To partly remediate this, channel belts from the channel belt dataset were categorised as high levees while natural levees from the geomorphological maps were categorised as low levees, based on the assumption that the main channel belt bodies have a higher sand content than the levees and are thus less susceptible to subsidence. However, this remains a rather simplistic way of mapping and will likely not always be a correct representation of the Roman palaeogeography. Along the boundary between the eastern and the central river area, the transition between the two mapping methodologies was smoothed by applying LIDAR elevation data and data from local research to identify elevation categories within the fluvial elements of the eastern river area map.

2.3.4.1 Mapping across the border: the northern district of Kleve

The eastern river area also includes the northern half of the German district of Kleve. This section was included for practical reasons: it is in close proximity to Nijmegen and lodged in between Doetinchem in the north, Cuijk in the west and Venray in the south, meaning that not including it could potentially affect future analyses. This section could be mapped using cross-boundary data from the channel belt dataset (Cohen *et al.* 2012) as well as local geomorphological information concerning the Pleistocene landforms from German research (Klostermann 1992; Shala 2001).

2.4 The palaeogeographic map

The palaeogeographic map constructed for the Middle Roman Period using the methodologies described above is presented in Figure 2.5. The next section will describe the units identified in the palaeogeographic map, regarding their morphology, genesis, lithology and vegetation during the Roman Period, as well as how these units relate to those in the earlier map of Van Dinter (2013). The subsequent sections will describe the distribution of these units through the western, central and eastern river area and will address some notable features or issues in the palaeogeographic reconstruction. More detailed information on the sources used for the reconstruction of each region can be found in Appendix 1.

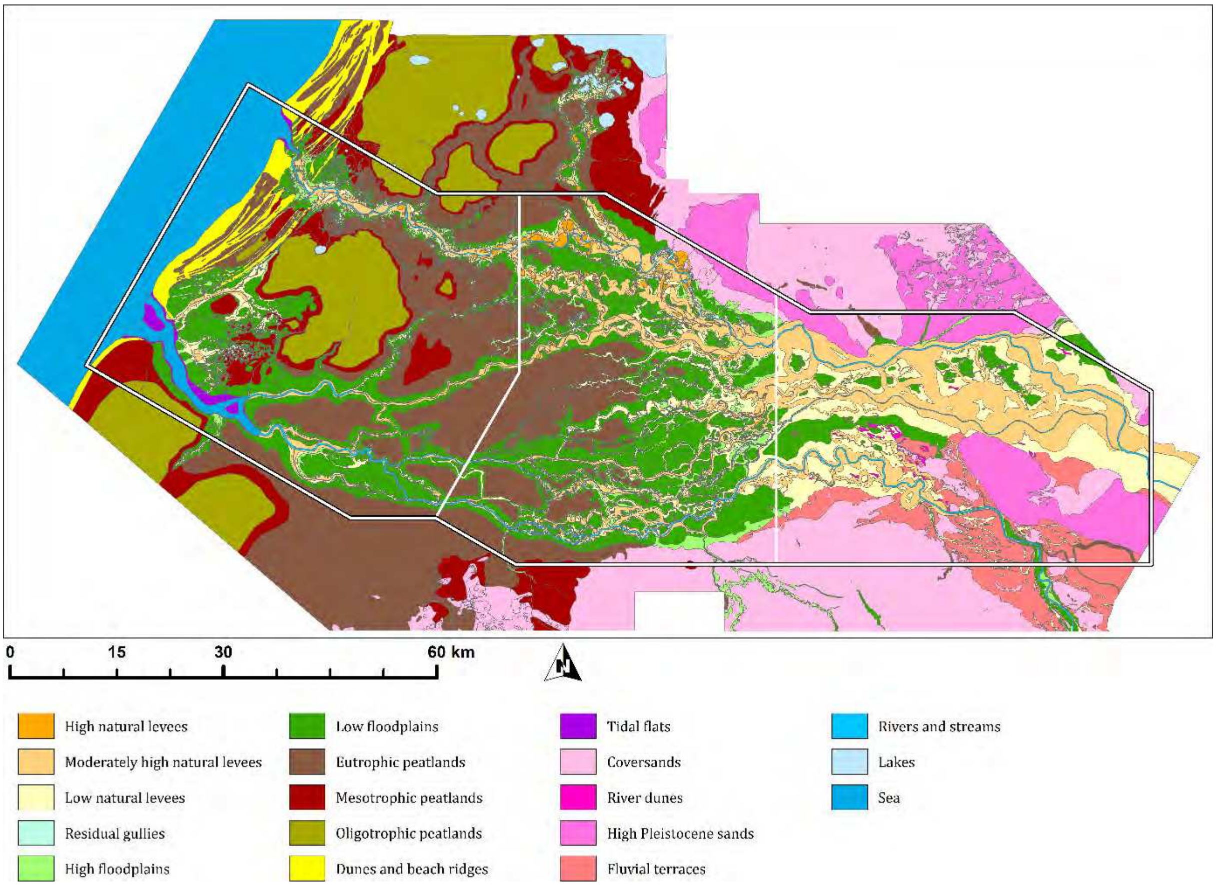


Figure 2.5. Natural palaeogeography of the Dutch limes *area in the Middle Roman Period, with rough boundaries of the western, central and eastern river area indicated.*

2.4.1 Palaeogeographic units

2.4.1.1 Natural levees

The first palaeogeographic element in the map is named ‘natural levees’. It correlates with the ‘natural levees’ and ‘alluvial ridge’ categories of Van Dinter (2013). Natural levees in physical geography are a familiar part of the facies-model for a meandering river in the Rhine-Meuse delta of the Netherlands (Fig. 2.6). They are formed during periods when high water of a river floods the surrounding fluvial plain. Once outside the river bed, the flow velocity of water decreases due to the present vegetation and the thinning volume of water. While coarse sand and gravel remains within the channel itself, fine sand, silt and clay fractions are transported into the fluvial plain. Most of this material is deposited directly next to the river bed, building an increasingly higher natural levee. Clay fractions can be transported further towards the flood basin basin (Berendsen 1982, 102–103) . Natural levees in the area are lithologically recognised as horizontally laminated sandy-silty clay with generally a fining-upwards sequence, occasionally containing layers of fine sand (Berendsen 1982, 103; Weerts 1996, 32). Natural levee deposits grade laterally into flood basin deposits.

Morphologically, natural levees in the Rhine-Meuse delta can be recognised as elongated ridges in the low-lying floodplain. Due to the many avulsions that have taken place in the Holocene, many of these ridges can be found in the fluvial plain of the Dutch river area downstream of the terrace crossing. The terrace crossing is the zone where a river shifts from erosion into the older deposits to the aggradation of new deposits. Nowadays, the terrace crossing of the Rhine is located near

Rees in Germany, but in the Roman Period this would have been located about halfway between Rees and the town of Lobith near the Dutch border (Cohen *et al.* 2009, 49). Upstream of this terrace crossing, fluvial deposits will have been confined to the narrow corridor in which the river cuts into older deposits, leaving elevated fluvial terraces on its sides. Within the study area such terraces can mainly be found near the Meuse river in the southeastern part of the study area.

Also included in the 'natural levees' palaeogeographic unit of this map are channel belt deposits and crevasse deposits, because they have a similar archaeological potential for habitation, agriculture and transport, and because they are sometimes difficult to differentiate on the basis of the source data. Natural levee deposits can be deposited on top of the channel belt deposits, making it difficult to distinguish between the two in cases with limited detailed information. Crevasse deposits are lithologically similar to natural levee deposits, and they can often be distinguished only based on their smaller thickness and extent (Berendsen 1982, 106; Weerts 1996, 32; Gouw and Erkens 2007, 26; Van Dinter and Van Zijverden 2010, 23). It has been shown that crevasse splays have an archaeological potential similar to natural levees, for instance regarding habitation (Van Dinter and Van Zijverden 2010). For these reasons, channel belt deposits and crevasse deposits are included in the palaeogeographic unit of 'natural levees' in the palaeogeographic map, as was done before in the earlier work by Van Dinter (2013).

In the facies-model for a meandering river, channel belt deposits by definition contain all deposits that are formed by the river within the river bed. Lithologically they consist mostly of sand and gravel (Berendsen 1982, 100; Weerts 1996, 32). Crevasse splays originate when lower parts of the natural levee are breached during periods of high water in the river. A complex of small channels is formed behind the breached natural levee, depositing sandy to silty clay on the floodplain and possibly sand within the crevasse channels.

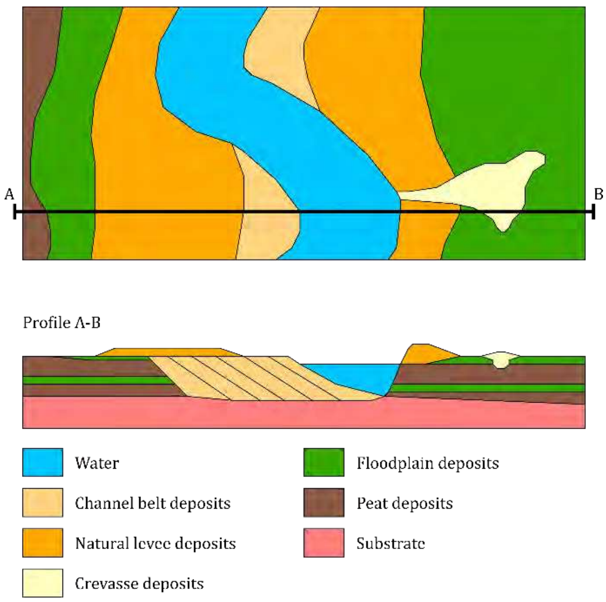


Figure 2.6. Schematic overview and cross-section of a meandering river in the Rhine-Meuse delta (adapted from Gouw and Erkens 2007, 27; after Weerts 1996, 53).

A final inclusion in the 'natural levees' unit are the sandy deposits that are formed within the channels of coastal inlets, such as the Gantel system in the vicinity of Den Haag (Vos *et al.* 2007). The (partially) abandoned channels have a similar morphology and lithology to natural levees, and had a similar potential for use in the past. Likewise, the marine clays that are deposited through the coastal inlets are categorised as part of the floodplains, as will be discussed in the corresponding section 2.4.1.2.

In the Dutch nomenclature of the shallow subsurface (Table 2.1; De Mulder *et al.* 2003; TNO 2013) natural levee, channel belt and crevasse deposits formed during the Holocene are mostly part of the Echteld Formation (Weerts and Busschers 2003a), with the exception of the fluvial deposits of the Meuse river upstream of the confluence with the Niers river near the modern town of Gennep. Since the Meuse river starts cutting through Rhine deposits downstream of this confluence they are both part of the Echteld Formation on the basis of lithological similarity. Upstream of the confluence, where there is little to no Rhine sediment, the fluvial deposits of the Meuse are classified under the Beegden Formation (Westerhoff and Weerts 2003).

Chronostratigraphy			**Lithostratigraphic units**							
			Marine	**Fluvial**				**Glacial**	**Other**	
				Baltic	**Rhine**	**Meuse**	**Belgian**			
Quarter-nary	**Holocene**		Naaldwijk		Echteld	Beegden	Kreekrak		Nieuw-koop	Boxtel
Quarter-nary	**Pleisto-cene**	**Late**	Eem		Kreftenheye	Beegden	Koewacht		Woudenb.	Boxtel
Quarter-nary	**Pleisto-cene**	**Mid-dle**		Appelscha	Kreftenheye; Urk; Sterksel	Beegden	Koewacht	Drente; Peelo		Boxtel

Table 2.1 Chronostratigraphic table of the lithostratigraphic formations in the Dutch nomenclature of the shallow subsurface (adapted from TNO 2013).

The natural levees, as well as the floodplains, have been subdivided in relative elevation classes using the LIDAR elevation data. Unfortunately, this image is obscured by the presence of urban development, post-Roman fluvial erosion and sedimentation, clay and sand extraction, and differential subsidence as a result of peat compaction (Van Asselen *et al.* 2009). These potential issues were already acknowledged by Van Dinter (2013, 14–15), and must be kept in mind when comparing areas where the elevation categories have been mapped in detail with areas where there is little to no apparent elevation difference.

Under natural conditions the levees carried an alluvial hardwood forest consisting of beech (*Fagus*), hazel (*Corylus*), lime (*Tilia*), birch (*Betula*), maple (*Acer*), hornbeam (*Carpinus*), ash (*Fraxinus*) and pine (*Pinus*) (De Klerk *et al.* 1997b, 144). However, these levees were mostly deforested already in the Iron Age through anthropogenic actions. In the Roman Period the semi-open parkland of the levees was finally transformed into a landscape of meadows and agricultural fields. Besides habitation, the levees were thus intensively used for agriculture, which is also evidenced by palynological research (Groot and Kooistra 2009; Kooistra *et al.* 2013, 7; Van den Bos *et al.* 2014).

2.4.1.2 Floodplains

The ‘floodplains’ palaeogeographic unit in this map actually covers two genetically different components. Firstly, it covers fluvial clay deposits formed as floodplains known from the facies-model for a meandering river, and secondly it covers marine clays that are deposited behind a closed coast through inlets. They are combined as they have a similar lithology and therefore a similar archaeological potential, but also because they are difficult to discern on the basis of the available source data. This unit is equal to the ‘flood basin’ category of Van Dinter (2013).

Morphogenetically, floodplains are deposits that are formed by fluvial processes outside the natural levees in the flood basin, where they form plains with a slight concave shape. When the water level in a river lowers after a period of high stand, the water in the flood basin becomes detached from the main channel. Within the stagnant water, massive to humic clay is deposited, and the thickness of these clay deposits generally decreases away from the river. Alternatively, under wet conditions with a low sedimentation rate organic matter can accumulate, causing peat formation. In the Dutch river area, flood basins almost always contain intertwined layers of peat and clay (Berendsen 1982, 108; Weerts 1996, 32). Similarly to other fluvial deposits, floodplain deposits are classified within the Echteld Formation (Weerts and Busschers 2003a).

The marine clays included in the ‘floodplains’ palaeogeographic unit are part of the Walcheren Member in the Naaldwijk Formation (Weerts 2003). They are deposited behind the closed coastline barriers through inlets. A good example is the Gantel system in the vicinity of the city of Den Haag, which is mapped in detail in the municipal geological map (Vos *et al.* 2007). The Walcheren Member consists of very fine to medium fine sand and sandy to silty clay. The sandy sediments are deposited within the channels of the inlet itself, and the clayey sediments are deposited outside the channels on the low-lying areas of the coastal plain. Depending on elevation above the low-lying plain, the sand deposits of the Walcheren Member are included in the ‘natural levees’ palaeogeographic unit, as (partially) abandoned channels have a similar morphology and lithology to natural levees.

Within the clay deposits of the flood basin a number of dark-coloured horizons can be found. These are identified as palaeo-A-horizons and were formed under influence of the vegetation during periods of low sedimentation. Laterally they are often connected to the top of peat layers (Berendsen 1982, 108). One of these horizons is dated to the Roman Period (Havinga and Op ’t Hof 1975, 263) and it is often found in local archaeological research (Fig. 2.7). Hypothetically this makes it suitable for reconstructing the palaeo-elevation of the floodplains and the flanks of natural levees, but its full potential has not been further explored in this study.

The vegetation in the floodplains can be characterised as marsh vegetation with locally open water present. The marsh vegetation consists of ferns (order of *Polypodiales*), grasses (*Poaceae*) and sedges (*Cyperaceae*) (De Klerk et al., 1997a, 156). Most naturally occurring woodlands, (primarily alder carr) disappeared before the Roman Period. The floodplains were unsuitable for arable agriculture, but could be used for lifestock grazing and the production of hay (Groot and Kooistra 2009).

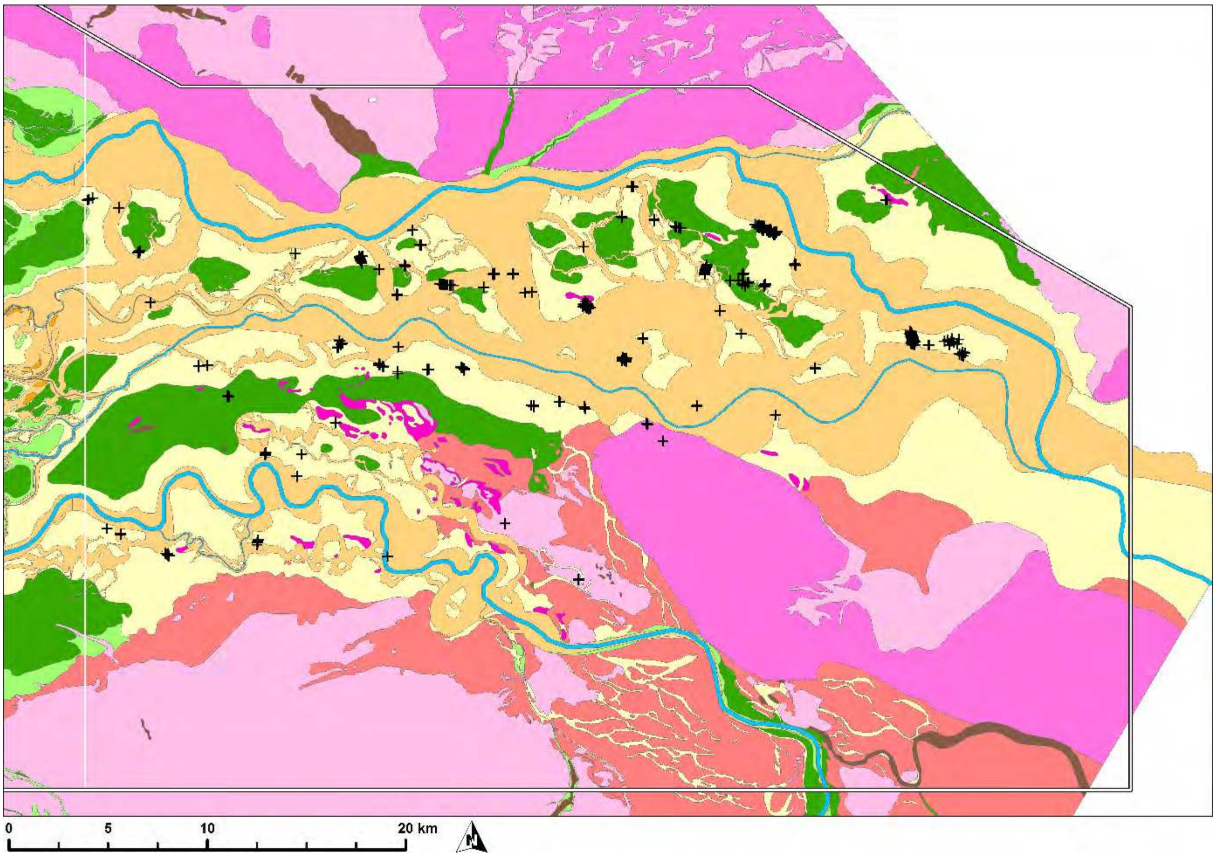


Figure 2.7. Inventory of locations where palaeo-A-horizons have been found in archaeological research in the eastern river area, based on archaeological reports available in EDNA up to October 2014. For palaeogeographic legend, see Fig. 2.5.

2.4.1.3 Peatlands

The peatlands category covers three palaeogeographic units subdivided on the nutrient level of the peat deposits, namely 'eutrophic peat', 'mesotrophic peat' and 'oligotrophic peat'. They correspond respectively to the 'fen woodland', 'reed and sedge swamp' and '*Sphagnum* peat dome' categories of Van Dinter (2013). This subdivision is made because these types of peatlands differ in vegetation, making the distinction relevant to research into aspects such as wood exploitation. In the Dutch nomenclature of the shallow subsurface peat deposits are classified as part of the Nieuwkoop Formation (Weerts and Busschers 2003b). Peat consist of (decayed) plant material and is formed in wet contexts where the decomposition of organic material is inhibited.

In the coastal area these wet conditions are caused by the rising sea level during the Holocene, which raised the groundwater level. When the coast closed the low-lying coastal flats behind the beach barriers became shallow water ponds, allowing for peat formation. The type of peat formed depends on whether there was still nutrient input from either sea or river flooding. If there was little input of nutrients, oligotrophic peat domes would have formed (Zagwijn 1986, 17).

In the fluvial area of the Rhine-Meuse delta the groundwater level was raised as a result of the gradient of the rivers decreasing due to the rising sea level. Peat was formed in the lowest parts of the flood basins where water stagnated. Peat deposits can occur here intercalated with clay deposits. Nutrient content in the groundwater decreased away from the river, creating a succession of eutrophic peat, mesotrophic peat and finally oligotrophic peat domes (Zagwijn 1986, 17; Pons 1992).

On the Pleistocene sands peat formation can also occur. Eutrophic peat can form in brook valleys under the influence of the nutrient-rich water. However, there are also other areas of poor drainage on the Pleistocene sands where nutrients are not available in such abundance, causing the formation of mesotrophic peat or even oligotrophic peat domes (Zagwijn 1986, 16).

The peatlands are a difficult part of the Dutch palaeogeography to map, considering that many have been exploited and subsequently disappeared after the Roman Period. Peatlands have been mapped using soil maps and geomorphological maps, with the addition of studies that look into peat extent in the past (e.g. Leenders 1996), the present (e.g. Stouthamer *et al.* 2008) or past peat exploitation (Bekius and Kooiman 2016). The distinction between different peats formed under different nutrient conditions has been made using soil map data, with the assumption that oligotrophic peat domes and the surrounding mesotrophic peatlands have been largely excavated and were located in the modern polders, following Van Dinter (2013, 15).

The peatlands were only exploited to a limited extent in the Roman Period due to the unsuitability for agriculture and the limited quality of the wood present. The vegetation that was present in the eutrophic peatlands in the Roman Period can be described as a fen woodland, as per Van Dinter (2013, 18). This closed woodland consisted mostly of alder (*Alnus sp.*) and/or willow (*Salix sp.*) with smaller amounts of oak (*Quercus sp.*), ash (*Fraxinus excelsior*) and elm (*Ulmus sp.*) (Pons and Van Oosten 1974, 21; Kooistra *et al.* 2006, 56; Bouma 2011, 159). In mesotrophic peatlands vegetation was dominated by reed (*Phragmites sp.*) and sedge (*Carex sp.*) plants (Pons and Van Oosten 1974, 21). The oligotrophic peat domes were largely made up of peat moss (*Sphagnum sp.*) with some heather species (*Ericaceae*) and occasionally birch (*Betula sp.*) (Pons and Van Oosten 1974, 21).

2.4.1.4 Dunes and beach ridges

The palaeogeographic unit of 'dunes and beach ridges' is found along the western coastline, and equals the category by the same name of Van Dinter (2013). Beach ridges are low and elongated ridges formed under the rising sea level in the Holocene, when the nearshore sedimentation rate exceeds the rate of sea level rise. Dunes are formed along the coast through aeolian processes involving mostly the sand of the beach ridges (Jelgersma *et al.* 1970, 98). They form elongated ridges reflecting the pattern of the underlying beach ridges, and are often separated by valleys filled with peat (Zagwijn 1984, 259). Dune and beach ridge deposits consist of very fine to medium fine sand. In the Dutch nomenclature of the shallow subsurface, dunes and beach ridges are considered part of the Zandvoort Member in the Naaldwijk Formation (Weerts 2003). In post-Roman times many of the dunes were buried under younger dune formation. The so-called Younger Dunes thus form an obscuring factor in the mapping of the Roman Period dune landscape. The Younger Dunes are quite different in morphology, being much higher and steeper and having parabolic dunes with a southwest-northeast orientation (Zagwijn 1984, 259–60). They are classified as the Schoorl Member in the Naaldwijk Formation (Weerts 2003).

The natural vegetation of the dunes in the Roman Period consisted of dune shrubs with sea buckthorn (*Hippophae*). It is an open landscape with a few trees, mostly juniper (*Juniperus*) and willow (*Salix*). Occasionally the vegetation was even sparse enough to allow for local drift sand activity (Flamman and Besselsen 2008, 67–68; Van Rijn 2011, 33).

2.4.1.5 Tidal flats

In the intertidal zone of the estuaries of Rhine and Meuse muddy tidal flats can be found. These clastic deposits are classified as part of the Naaldwijk Formation (Weerts 2003). Mapping the shape of this morphological element comes with a lot of uncertainty, since it changes constantly over short time spans. It corresponds to the 'tidal flats' deposit of Van Dinter (2013).

2.4.1.6 Coversands

The palaeogeographic unit of 'coversands' covers all landforms known as coversands, which were formed as layers of well-sorted fine to medium coarse sand deposited through aeolian processes during the Weichselian. Within the Netherlands they are expressed both as extended sheets of sand as well as elongated ridges and valleys (Van der Hammen and Wijmstra 1971, 66). Coversands are classified as the Wierden Member within the Boxtel Formation (Schokker 2003; Schokker *et al.* 2005).

This unit was not originally distinguished in the palaeogeographic map of Van Dinter (2013), where it was classified as part of the 'Higher Pleistocene grounds' instead. This was likely done because it did not affect the subsequent analysis in that research. However, since the vegetation cover and archaeological potential of coversands is different from the other Pleistocene sands which can potentially affect future applications, in this map the 'coversands' unit was established to accommodate these dissimilarities.

The Pleistocene sand areas, including the coversands, have been mapped using primarily geomorphological maps and soil maps. One obscuring factor here is the presence of drift sand deposits, which have been formed from Medieval times onwards and regularly hide the transition from the floodplains to the coversands that would have been present in the Roman Period. Wherever possible, drift sand deposits were recognised using a combination of the geomorphological maps and soil maps to find sand deposits with little soil formation, as well as using LIDAR elevation data to find a pronounced dune relief that can be found in drift sand deposits but which is not as common in coversand deposits (Koster 1982, 127; Koster *et al.* 1993, 248).

Research on the coversands in the south of the research area have shown an open forest vegetation during the Roman Period, consisting primarily of oak (*Quercus*) with lower amounts of hazel (*Corylus*), birch (*Betula*) and pine (*Pinus*). The deforestation that caused this open forest vegetation largely occurred already in the Bronze Age (Van Beurden 2002, 278–280). In the southwest, the coversands had an alternation of an open landscape and a moderately dense woodland, although the amount of woodlands seems to decline during the transition from the Iron Age to the Roman Period due to a more intensive agricultural use of the landscape (Kooistra 2008, 120–121). The brook valleys mostly contained an alder carr vegetation, although this was at least partially replaced by grasses in the Iron Age and its presence declined further during the Roman Period due to a use as pasture (Kooistra 2008, 120–121).

2.4.1.7 River dunes

The palaeogeographic unit of 'river dunes' covers the aeolian landforms found in the floodplain of the Rhine-Meuse delta, deposited along the courses of braided river systems during the Late Weichselian glaciation. They can be distinguished from the aeolian coversand deposits based on their slightly coarser lithology, as they largely consist of reworked fluvial sediment (Törnqvist *et al.* 1994). In the central river area river dunes are mostly found locally as 'islands' of sand, and are partially covered by younger floodplain deposits. Still, they can rise several metres above the plain making them distinctive landmarks. In the eastern river area larger expanses of river dunes are found at the surface. River dunes are classified as the Delwijnen Member within the Boxtel Formation (Schokker *et al.* 2005).

This unit was not distinguished in the map of Van Dinter (2013) as river dunes do not occur at the surface in the Old Rhine area but are buried under younger deposits.

2.4.1.8 High Pleistocene sands

The 'high Pleistocene sands' palaeogeographic unit consists of a number of different morphological units. It correlates with the 'higher Pleistocene grounds' category of Van Dinter (2013) with the exclusion of coversands, which have been introduced earlier as a separate unit. In general, they are all associated with the push moraines of 't Gooi, the Utrechtse Heuvelrug, the Veluwe and the Nijmegen-Kleve ridge. Push moraines are ridges formed along the ice margin by the deformation of ice and sediment (Bennett 2001, 199). The push moraines in the central Netherlands were formed during the Drenthe advance of the Saalian glaciation and consist of a series of nappes that were displaced horizontally. The nappes can consist of (glacio-)fluvial or older Tertiary sands and gravel that have been displaced over a layer of fine-grained sediment (Van der Wateren 1995, 106–107; Bennett 2001, 219). The pushed deposits of the Veluwe and the Utrechtse Heuvelrug are largely fluvial in nature, involving mostly Rhine and some Meuse sediment from the Early Pleistocene Waalre Formation and the Middle Pleistocene Sterksel and Urk Formations (Berendsen 2004, 44).

After their initial formation the push moraines have undergone a number of other processes, forming different landforms over the older structure. Meltwater of the Saalian ice sheet has created glaciofluvial deposits in the form of sandrs and occasionally a kame terrace (Maarleveld 1955; Augustinus and Riezebos 1971). In the Dutch nomenclature of the shallow subsurface they form the Schaarsbergen Member in the Drente Formation (Bakker *et al.* 2003). During the Weichselian the ice sheet did not reach as far as the Netherlands, yet periglacial conditions were present during this time. Water from snowmelt was forced to run-off over the surface due to the permafrost subsoil, carving elongated valleys down the slopes of the push moraines. Due to the lithological similarities and since these landforms are functionally part of the pushed moraine, they have not been differentiated within the palaeogeographic unit of 'High Pleistocene sands'.

Research on the Pleistocene sands of the Veluwe has shown that the vegetation at the start of the Roman Period consisted of an open forest, with heath and grasses and isolated patches of trees including beech (*Fagus*) and hazel (*Corylus*) (Hulst 2007, 63–64, 68). This did not change in the Roman Period, as this part of the landscape was likely only sparsely exploited.

2.4.1.9 Fluvial terraces

The palaeogeographic unit of 'fluvial terraces' comprises the series of fluvial terraces consisting of material deposited during the Pleistocene. They are mostly elevated above the Holocene floodplain and are found upstream of the terrace crossing in the vicinity of Nijmegen, as they are formed through incision of the meandering river. The Holocene activity of the Meuse is therefore limited to its current valley (Tebbens *et al.* 1999). The fluvial terraces mostly consist of coarse to very coarse sand, and are classified as part of the Beegden Formation (Westerhoff and Weerts 2003).

Fluvial terraces were not included as a category in the palaeogeographic map of Van Dinter (2013), since these landforms are not found in the Old Rhine area.

The vegetation development of the fluvial terraces is similar to that of the coversands. Up until the Bronze Age, the higher terraces around the Meuse were covered in a deciduous forest dominated by oak (*Quercus*) and hazel (*Corylus*). From the Bronze Age but especially from the Iron Age the forests became more open through small-scale agriculture and grazing activity. Starting in the Roman Period, large-scale deforestation took place, likely due to intensive agricultural activity (Zuidhoff and Huizer 2015, 79).

2.4.1.10 Rivers and streams

The 'rivers and streams' palaeogeographic unit includes all manners of fluvial surface water, ranging from the largest rivers including Rhine and Meuse to small Pleistocene brooks and crevasse splay drainage water. To establish which rivers were active during the Roman Period the acctive channel belts from the dataset of Cohen *et al.* (2012) are used. Where possible, residual channels were mapped using the LIDAR-derived elevation data. The dating of crevasse splays is more difficult, so following Van Dinter (2013, 15) the assumption is made that most crevasse splays visible in the elevation data were formed just prior or during the first centuries AD and are thus included in the palaeogeographic map.

In the following descriptions of the reconstructed palaeogeography the rivers and streams will be referred to using mostly the names assigned to the channel belts in the dataset of Cohen *et al.* (2012), which are themselves continuations of naming traditions used by Berendsen and Stouthamer (2001), Berendsen (1982) and Vink (1926). In this dataset channel belts that are active up to the present retain their modern names, such as the Meuse, Waal, Lek, Kromme Rijn, Hollandse IJssel and Linge, while abandoned channel belts are named after local toponyms.

2.4.2 Western river area

For the purpose of a detailed description of the reconstruction of the natural palaeogeography in this section and to more easily group the sources used in the reconstruction of the palaeogeographic map, the western, central and eastern river areas have been subdivided into a number of smaller regions (Fig. 2.8). The use of these regions for the description of the sources used in the reconstruction can be found in Appendix 1. The regions will not be used for any analyses in subsequent chapters. For the western river area, in the order in which they will be described here, they are 'Old Rhine', 'Meuse estuary', 'western Meuse', 'Hollandse IJssel', 'western Lek' and 'southwestern peatlands'.

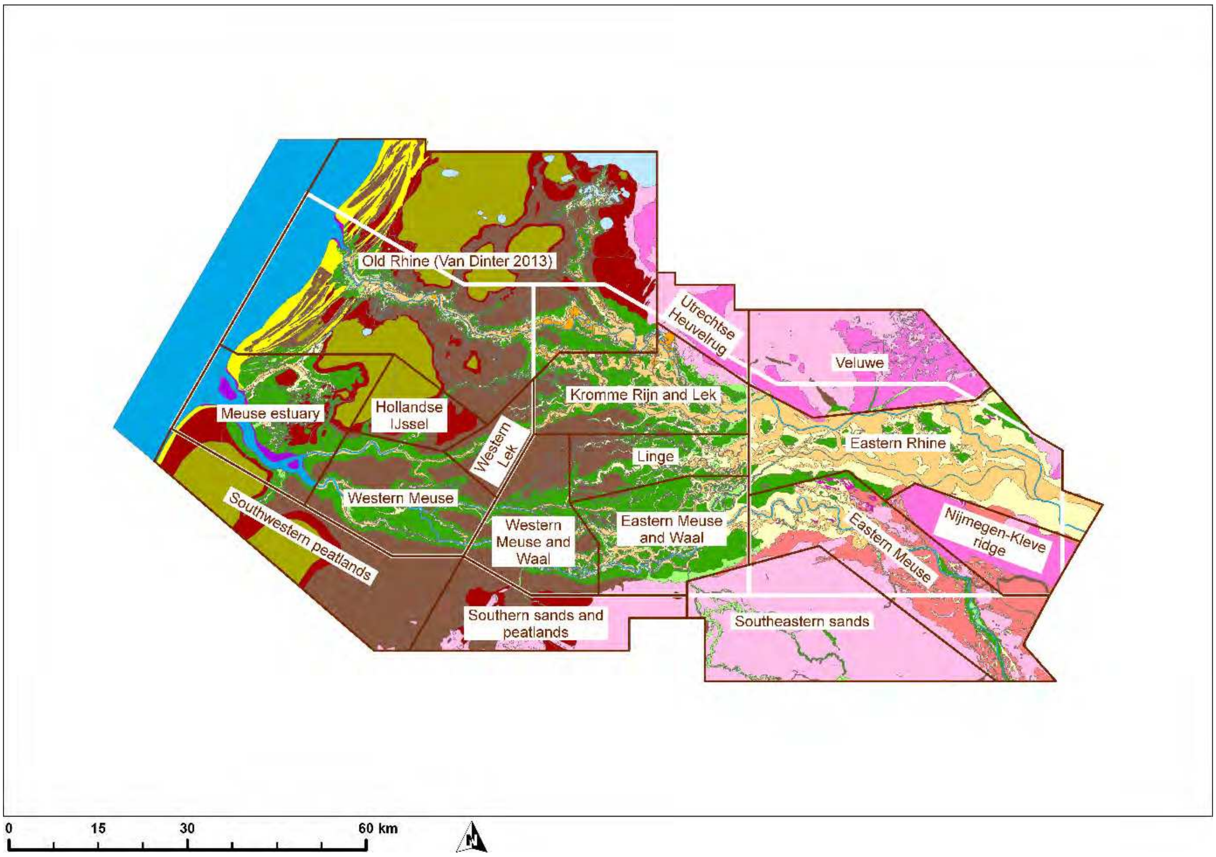


Figure 2.8. Subdivision of the research area into smaller regions for descriptive purposes.

2.4.2.1 Old Rhine (Fig. 2.9)

The Old Rhine downstream from Utrecht was already mapped by Van Dinter (2013). The palaeogeographic map from that research overlaps parts of the western and central river area, and was thus incorporated into this reconstruction, with some notable changes and some very minor changes. The former include the division of the 'higher Pleistocene grounds' into the 'high Pleistocene sands' and 'coversands' units, modification of the peat extent at the southern edge of Van Dinter's research area, and modification of the coastline near the Rhine estuary based on the assumption that the Roman coastline was located further offshore, for instance given the location of the eroded *castellum* of Katwijk-Brittenburg (Bloemers and De Weerd 1984, 47).

The issue of the coastline was already acknowledged by Van Dinter (2013, 18), but not yet made explicit by mapping the eroded areas, rather showing an outline of the former coast. Due to the nature of the spatial analyses to be applied on the palaeogeographic map, it was necessary to explicitly map these areas as well. The coastal reconstruction is based on the map by Vos and De Vries (2013).

2.4.2.2 Meuse estuary (Fig. 2.10)

This region is dominated by the large estuary in which water from the Meuse as well as the Rhine through the Waal, Lek (but see the 'western Lek' section) and Hollandse IJssel enters the ocean (Tacitus, *Ann.* II, 6). In the Roman Period this estuary was also known as the *Helinium* (Plinius, *NH* IV, 101). Another prominent feature is the Gantel system, which was originally a tidal channel coming from the estuary and spreading into several smaller channels further inland. It came into existence during the Iron Age and eroded much of the peat originally present in the area. During the Roman Period the Gantel system was largely abandoned with only smaller creeks remaining, and the preserved channel belts became elevated parts of the landscape suitable for habitation (Kerkhof *et al.* 2010, 31; Cohen *et al.* 2012, ID 406). An older system of tidal channels is located south of the Gantel, and also featured as an elevated area suitable for habitation in the Roman Period (Kerkhof *et al.* 2010, 29, 31). A number of smaller channels are located further east, known as the Vlaarding, Harg and Schie as well as the Rotte further upstream, which are all former peat drainage channels that developed into tidal channels under the influence of the Meuse estuary (Cohen *et al.* 2012, IDs 418–20, 427).

The Gantel also formed the southwestern starting point of the *Fossa Corbulonis*, an artificial waterway constructed around AD 50 and connecting two tidal creeks of the Meuse and Rhine estuaries respectively (De Kort and Raczynski-Henk 2014). There may have been a second partly artificial waterway on the south side of the Meuse, connecting the Meuse to the Scheldt (De Bruin *et al.* 2012), although due to the large amount of post-Roman erosion this is difficult to substantiate.

2.4.2.3 Western Meuse (Fig. 2.11)

This region is a very complex area with multiple contemporary channels. The Meuse is joined by the Waal and the Lek is joined by the Hollandse IJssel, before both drain into the Meuse estuary in the west. There are also a number of smaller channels branching off and rejoining the Meuse in this area. This information is based on the channel belt palaeogeography of Cohen *et al.* (2012). However, there is some uncertainty regarding the role of the Lek in the Roman Period. This issue will be further discussed in the description of the 'western Lek' region.

The confluences of these channels as well as tidal influences from the Meuse estuary have allowed for the formation of relatively large floodplains with many crevasses, in contrast to the more upstream areas of these rivers where the clayey floodplains are narrower.

2.4.2.4 Hollandse IJssel (Fig. 2.12)

The Hollandse IJssel is a smaller distributary of the Rhine delta that flows into the Meuse estuary. It formed not long before the start of the Roman Period, and likely captured a small peat drainage channel, similar to channels such as the Rotte, into the estuary (Cohen *et al.* 2012, ID 68). The Rotte can also be found in this region, draining the oligotrophic and mesotrophic peatlands between the Rhine, Meuse and Hollandse IJssel. The Hollandse IJssel is marked by a number of crevasse splays, indicating that tidal backwater also had some effect here (Van Dinter 2013, 19).

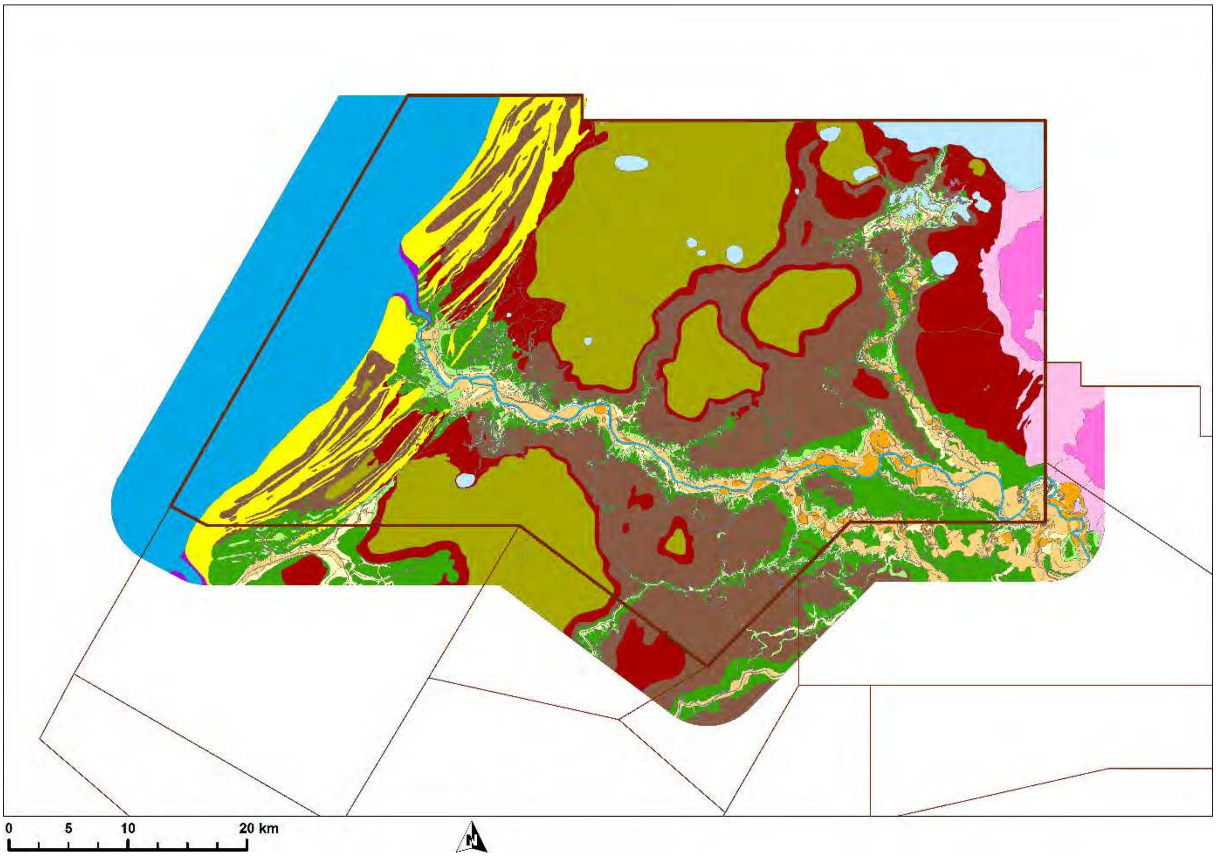


Figure 2.9. Palaeogeography of the 'Old Rhine' region, primarily from Van Dinter (2013). For legend see Fig 2.5.

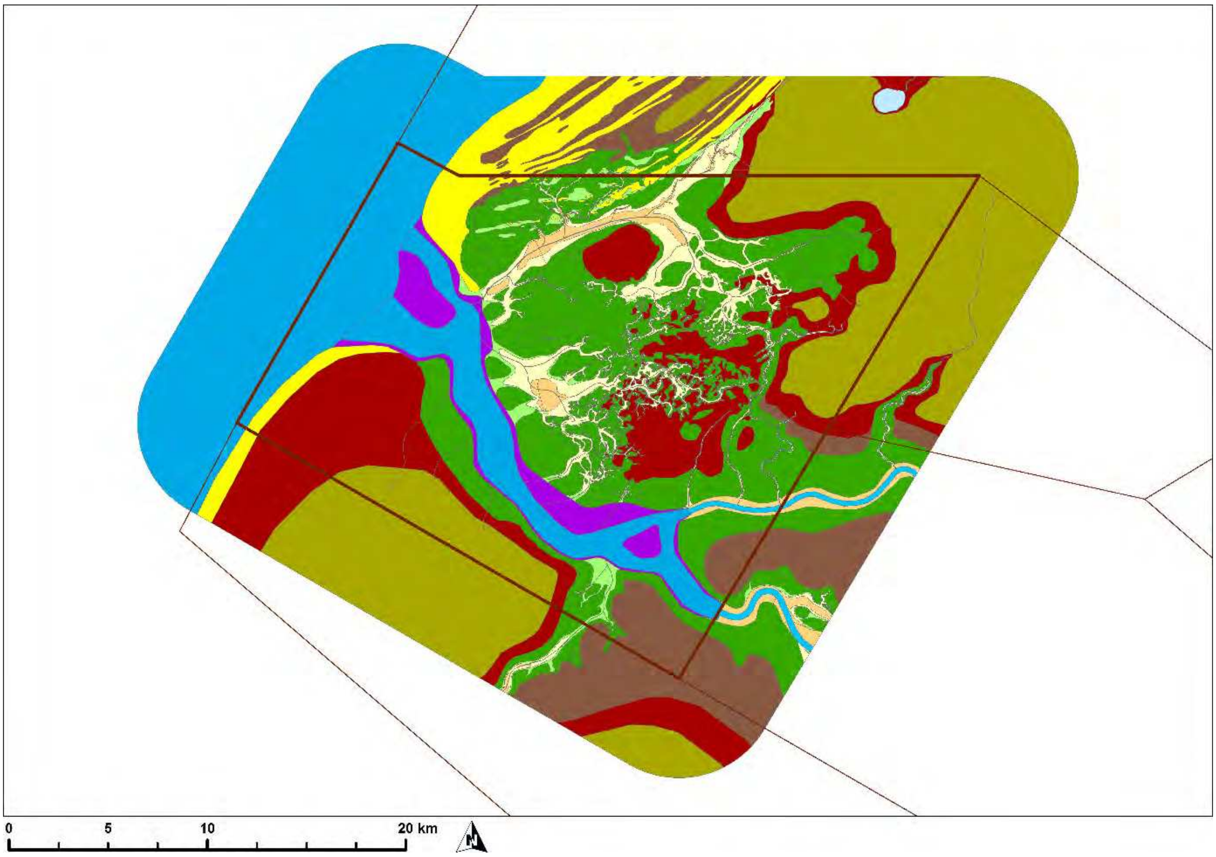


Figure 2.10. Palaeogeography of the 'Meuse estuary' region. For legend see Fig 2.5.

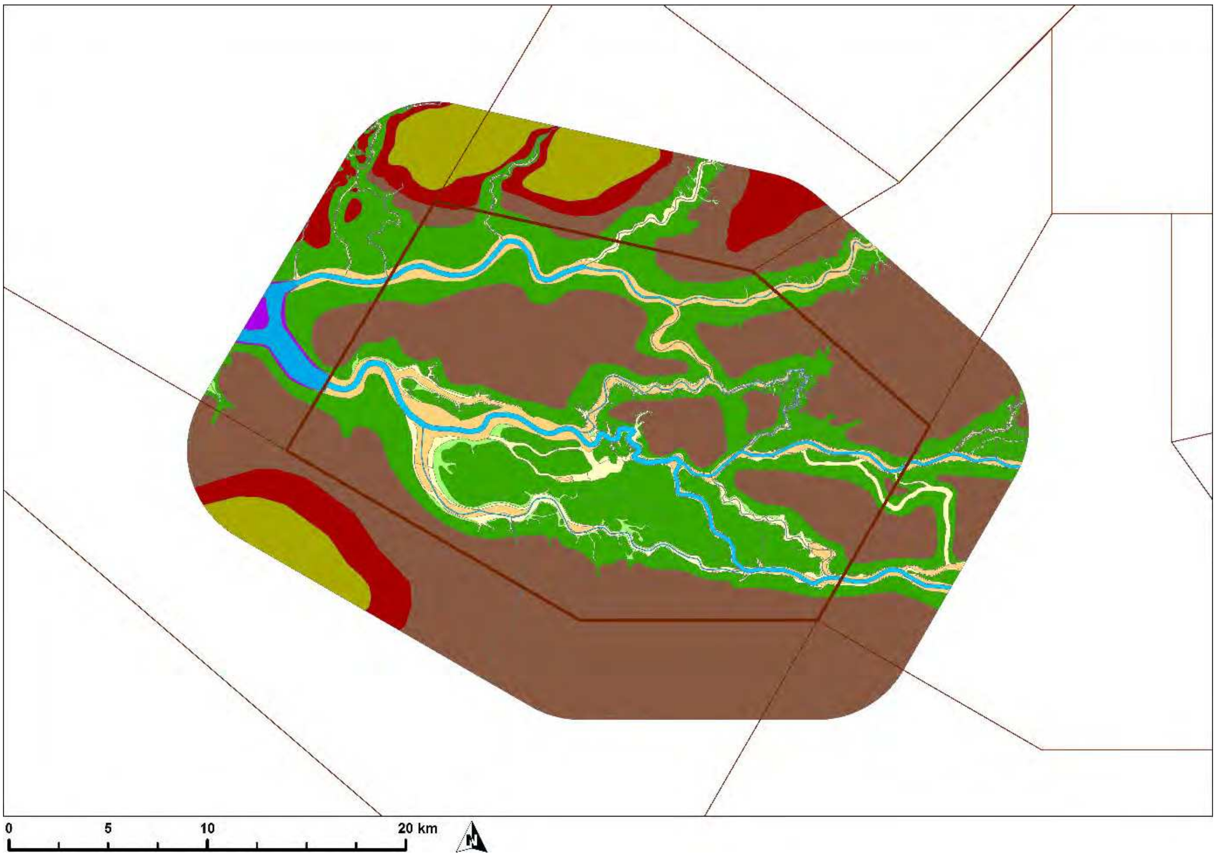


Figure 2.11. Palaeogeography of the 'western Meuse' region. For legend see Fig 2.5.

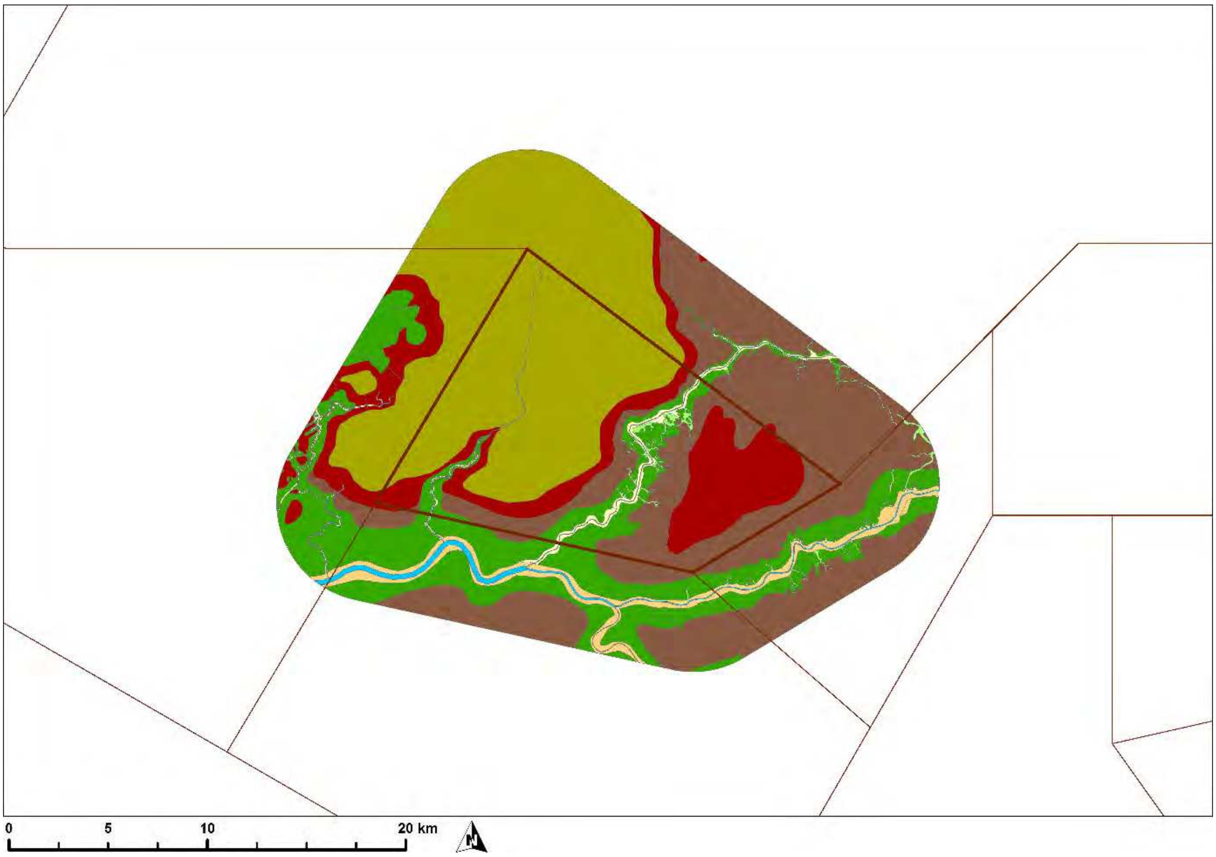


Figure 2.12. Palaeogeography of the 'Hollandse IJssel' region. For legend see Fig 2.5.

2.4.2.5 Western Lek (Fig. 2.13)

From a palaeogeographic point of view the Lek is one of the most problematic rivers. There is currently no consensus over the activity of this river during the Roman Period. Cohen *et al.* (2012, 91) give ^{14}C-dates for the beginning of sedimentation of 1950 ± 30 BP and 2220 ± 35 BP, placing it in or slightly before the Roman Period. This is not necessarily the same as the birth of the river, as it is possible for sedimentation to start at a later time. In this scenario it is possible that the Lek is not present during the Early Roman Period but is present in the Middle Roman Period. Furthermore, Vos and De Vries (2013) do not include the Lek in their palaeogeographic reconstruction of AD 100.

To deal with the uncertainty involving the Lek, an alternative scenario was constructed that can be implemented in the 'default' palaeogeographic map. The default palaeogeographic map, aiming to show the palaeogeography of the Middle Roman Period, includes the Lek as an active river as well as the fluvial deposits that are the result thereof. The alternative scenario, reflecting an Early Roman Period and perhaps early Middle Roman Period without an active Lek river, contains a landscape consisting primarily of peat assumed to be present before erosion by the Lek (Fig. 2.14). This does not only affect the area covered by the region defined here as 'western Lek', but also covers the course of the Lek upstream until the point where it departs from the Rhine. For spatial analyses, both scenarios can be used depending on the chronological context used and assumptions made regarding the age of this river.

2.4.2.6 Southwestern peatlands (Fig. 2.15)

Between the Meuse and Scheldt rivers and the coversands of the southern Netherlands a large extent of peatland is found. Nowadays much of this has disappeared under a layer of clay due to marine inundation after the Roman Period (Vos and Van Heeringen 1997). Similar to other coastal areas in the Netherlands, a mesotrophic to oligotrophic peat developed behind the coastal barriers. This peatland was drained by small peat drainage channels, as well as through brooks coming from the coversands in the southeast of this region. As has been mentioned in the 'Meuse estuary' section, it is possible that there was a partly artificial waterway connecting the Meuse to the Scheldt river (De Bruin *et al.* 2012) but this is difficult to map due to the uncertainty in location. Since the Scheldt is outside the research area, this waterway was omitted.

2.4.3 Central river area

The central river area is subdivided into the regions 'Utrechtse Heuvelrug', 'Kromme Rijn and Lek', 'Linge', 'western Meuse and Waal', 'eastern Meuse and Waal' and 'southern sands and peatlands'. A small part of the 'Old Rhine' region described in the previous section also lies within the borders defined for the central river area. This region was already mapped by Van Dinter (2013).

2.4.3.1 Utrechtse Heuvelrug (Fig. 2.16)

The Utrechtse Heuvelrug is a push moraine rising up to almost 70 metres above the fluvial plain of the Old Rhine. Its flanks are buried under coversand deposits. With the exception of post-Roman drift sand activity, from a geomorphological point of view this region looked very much the same in the Roman Period as it does today.

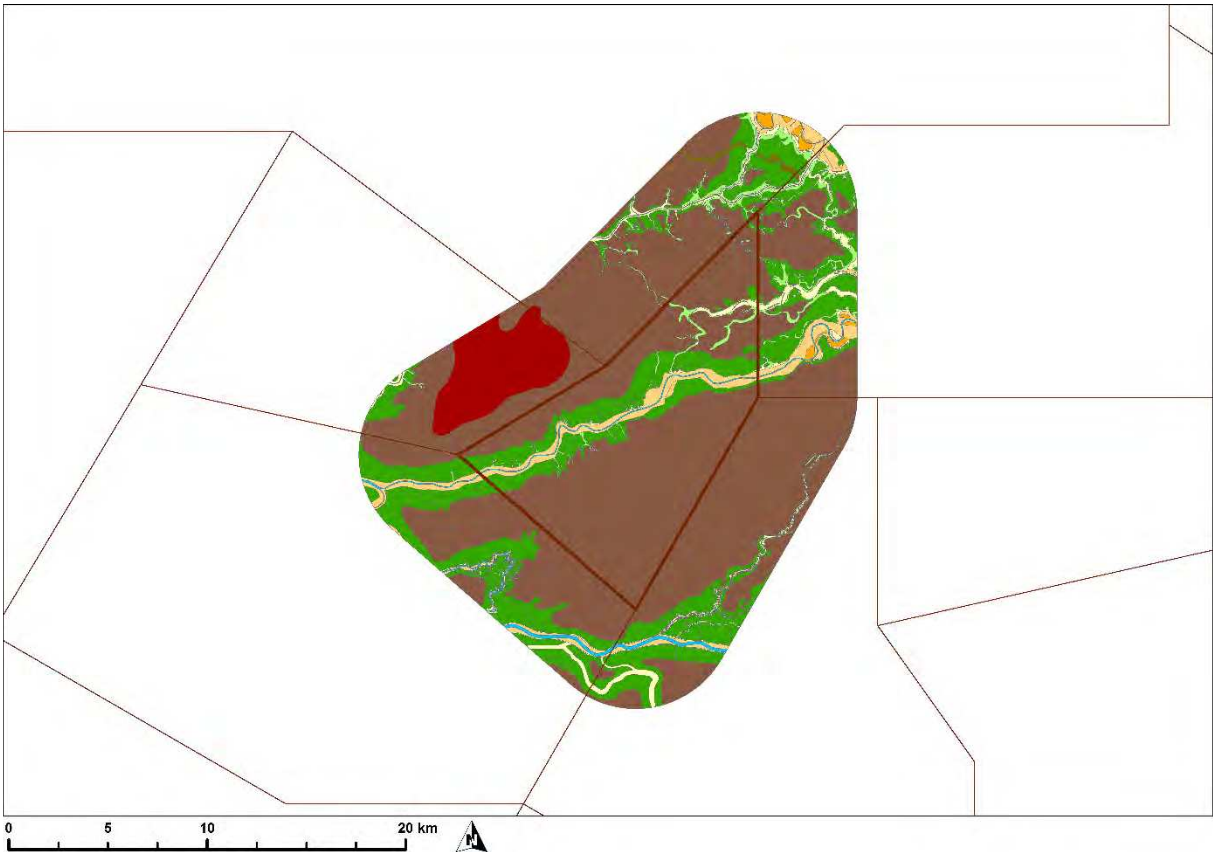


Figure 2.13. Palaeogeography of the 'western Lek' region. For legend see Fig 2.5.

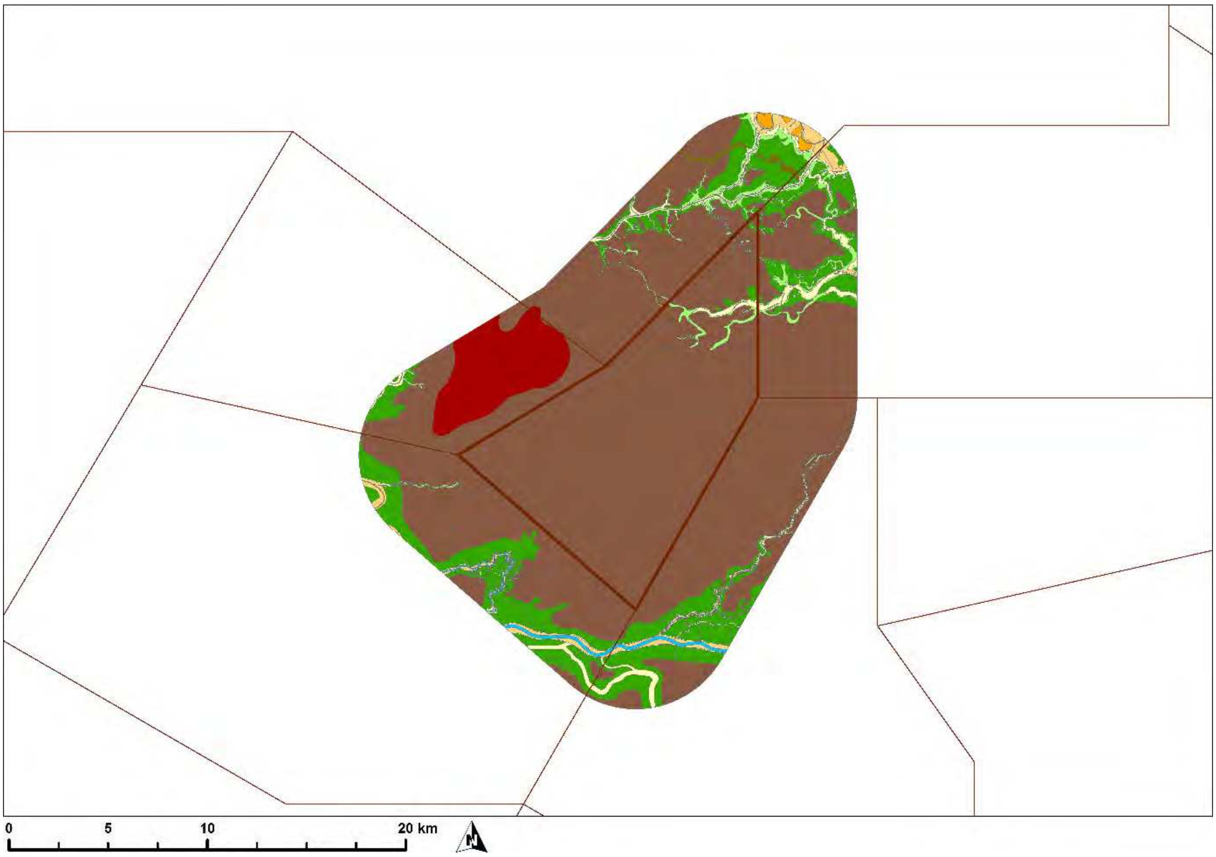


Figure 2.14. Palaeogeography of the 'western Lek' region without an active Lek river. For legend see Fig 2.5.

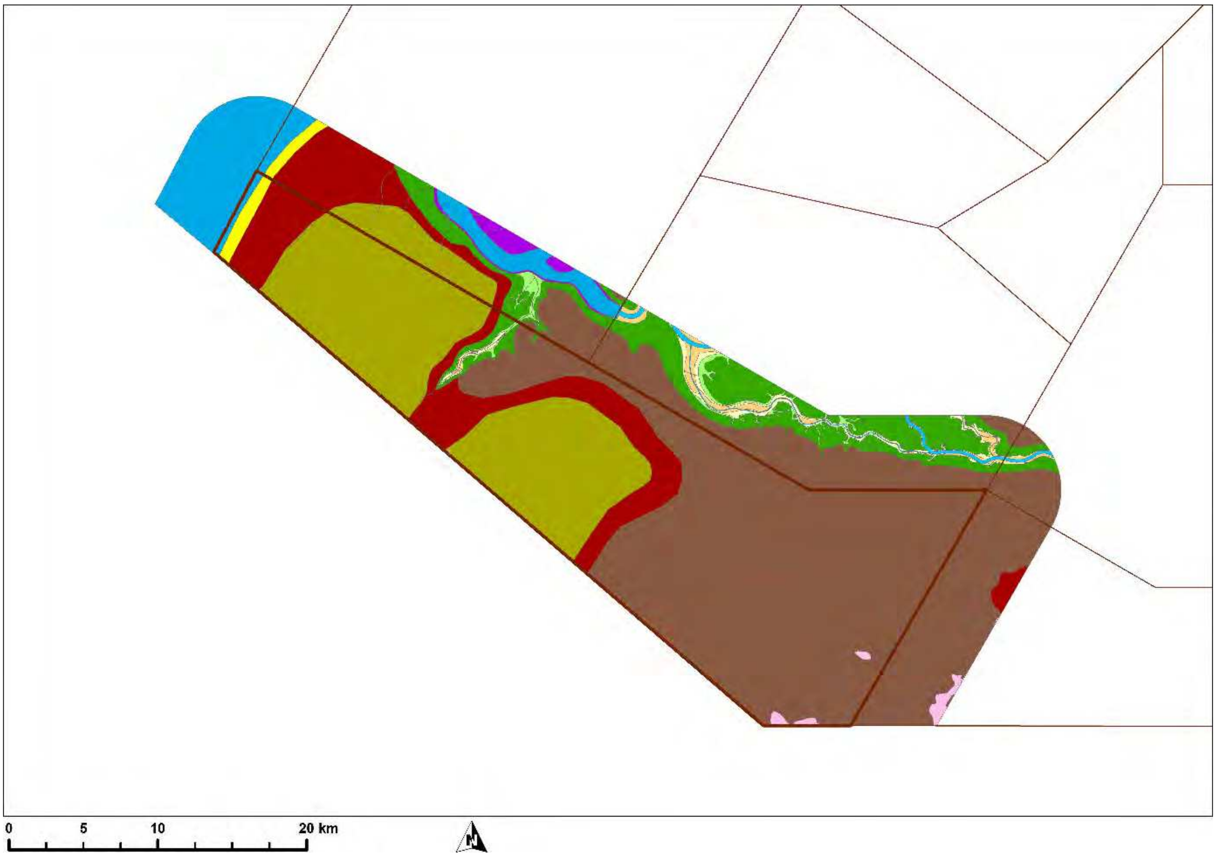


Figure 2.15. Palaeogeography of the 'southwestern peatlands' region. For legend see Fig 2.5.

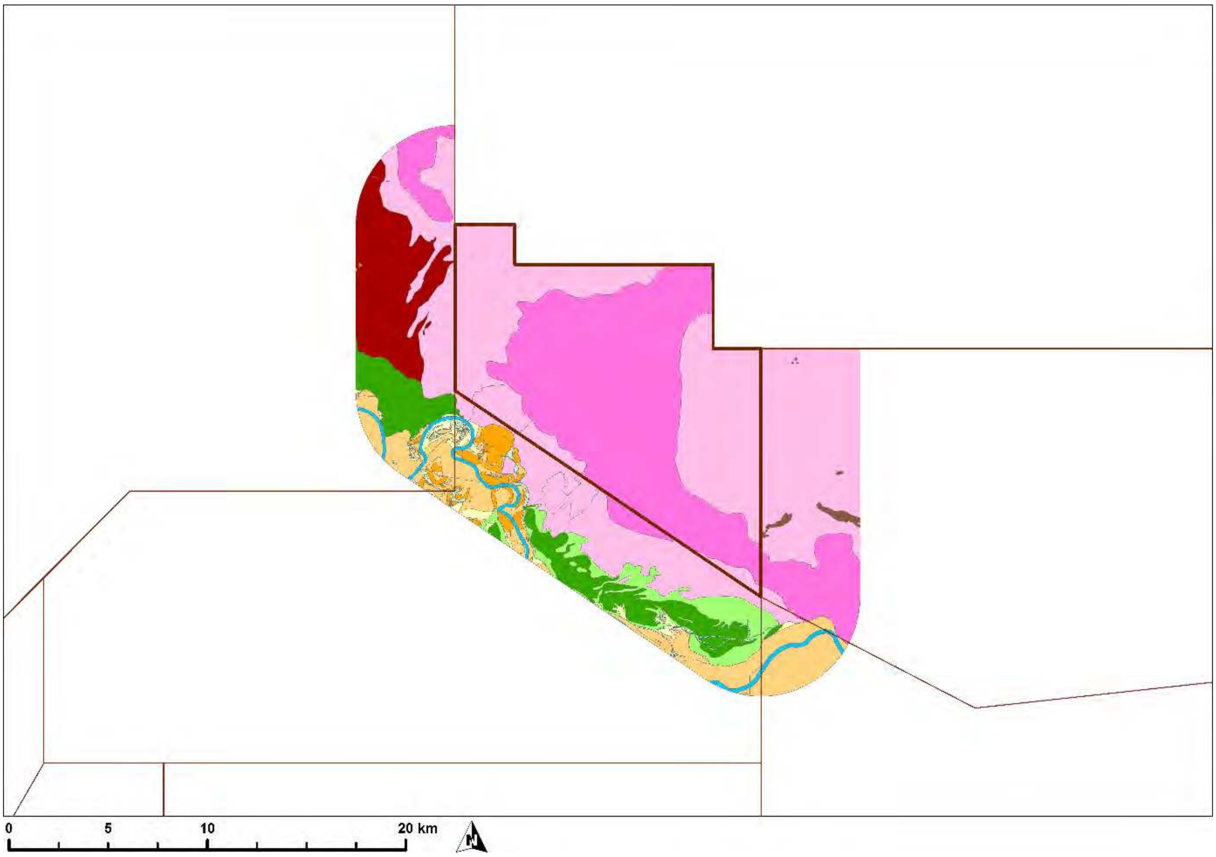


Figure 2.16. Palaeogeography of the 'Utrechtse Heuvelrug' region. For legend see Fig 2.5.

2.4.3.2 Kromme Rijn and Lek (Fig. 2.17)

The 'Kromme Rijn and Lek' region has been studied in quite some depth both in physical geography (e.g. Berendsen 1982) as well as archaeology (e.g. Vos 2009). During the Roman Period this area is characterised by wide stream ridges and levees of the Rhine (locally known as the Kromme Rijn) as well as abandoned channel belts. Deposits of those on which Roman habitation was found include the Werkhoven, Houten, Jutphaas, Vuylkop, Honswijk and Blokhoven channel belts (Cohen *et al.* 2012, IDs 22, 70, 74, 78, 173, 181). Floodplains are found between the levees of these belts.

Another important feature in the region is the river Lek. The age of this river has already been discussed in the 'western Lek' section. In the default scenario the Lek and its fluvial deposits are included in the palaeogeographic map. Prior to the onset of the Lek river, there was already a distributary of the Rhine flowing roughly along the course of the current Lek and onwards through the Hollandse IJssel, which is reflected in the alternative scenario (Fig. 2.18).

2.4.3.3 Linge (Fig. 2.19)

The Linge was one of the larger channels of the Waal branch of the Rhine during the Late Iron Age, but was gradually surpassed by the Waal course further south, which is reflected in this palaeogeographic reconstruction of the Middle Roman Period. Another channel branches off from the Linge northwards to the Lek, through the Buren channel belt (Cohen *et al.* 2012, ID 34). The flood basin between the Linge and the Lek is crossed by a number of smaller and mostly abandoned channel belts (Gouw and Erkens 2007, 33). Within this region, the basin along the eastern part of the Linge is filled with clayey deposits, while in the west peatlands are present.

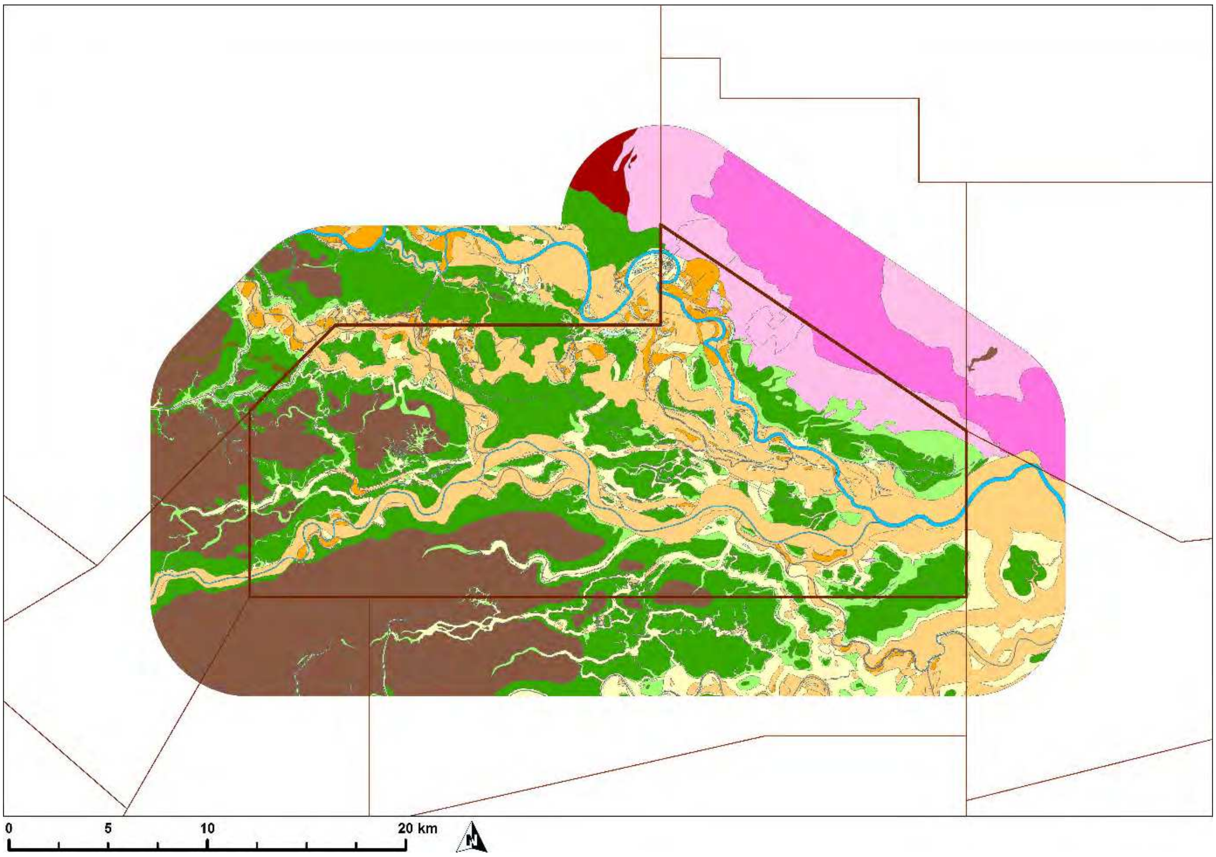


Figure 2.17. Palaeogeography of the 'Kromme Rijn and Lek' region. For legend see Fig 2.5.

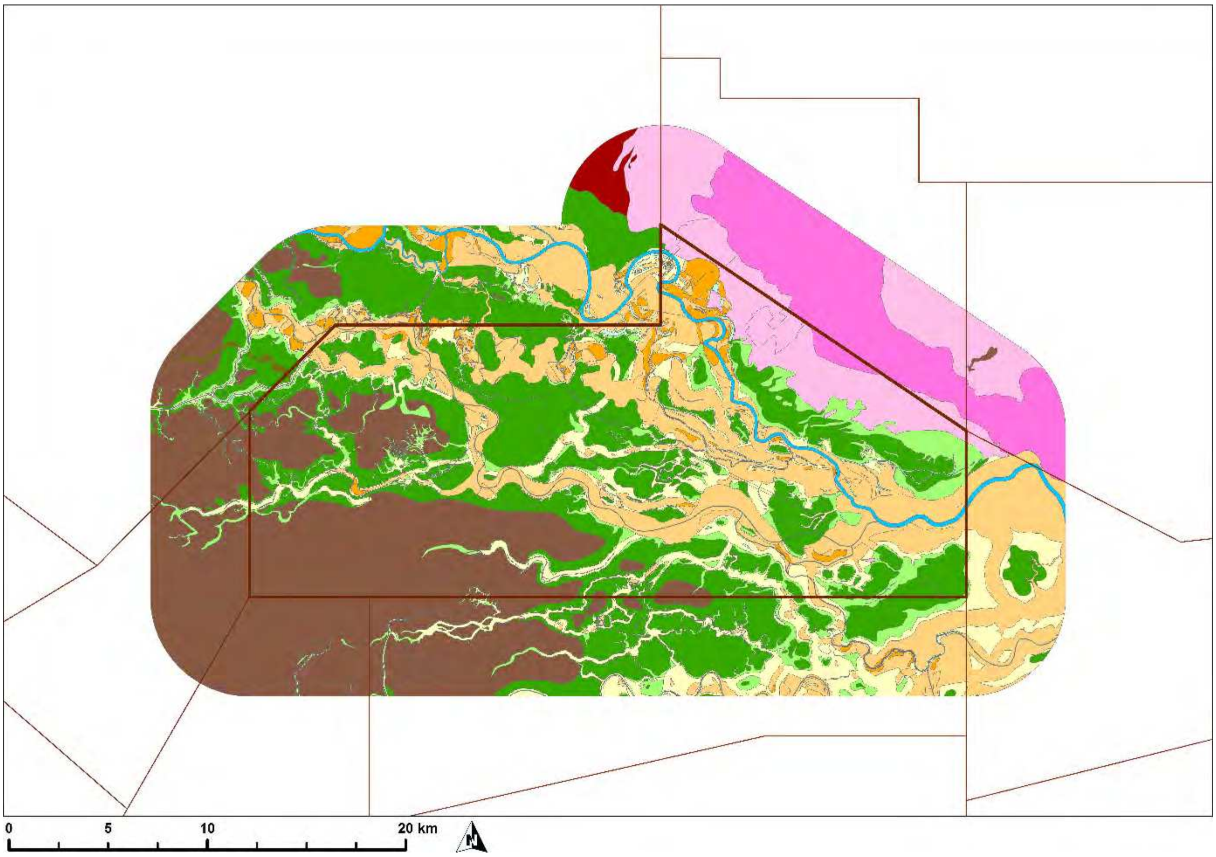


Figure 2.18. Palaeogeography of the 'Kromme Rijn and Lek' region without an active Lek river. For legend see Fig 2.5.

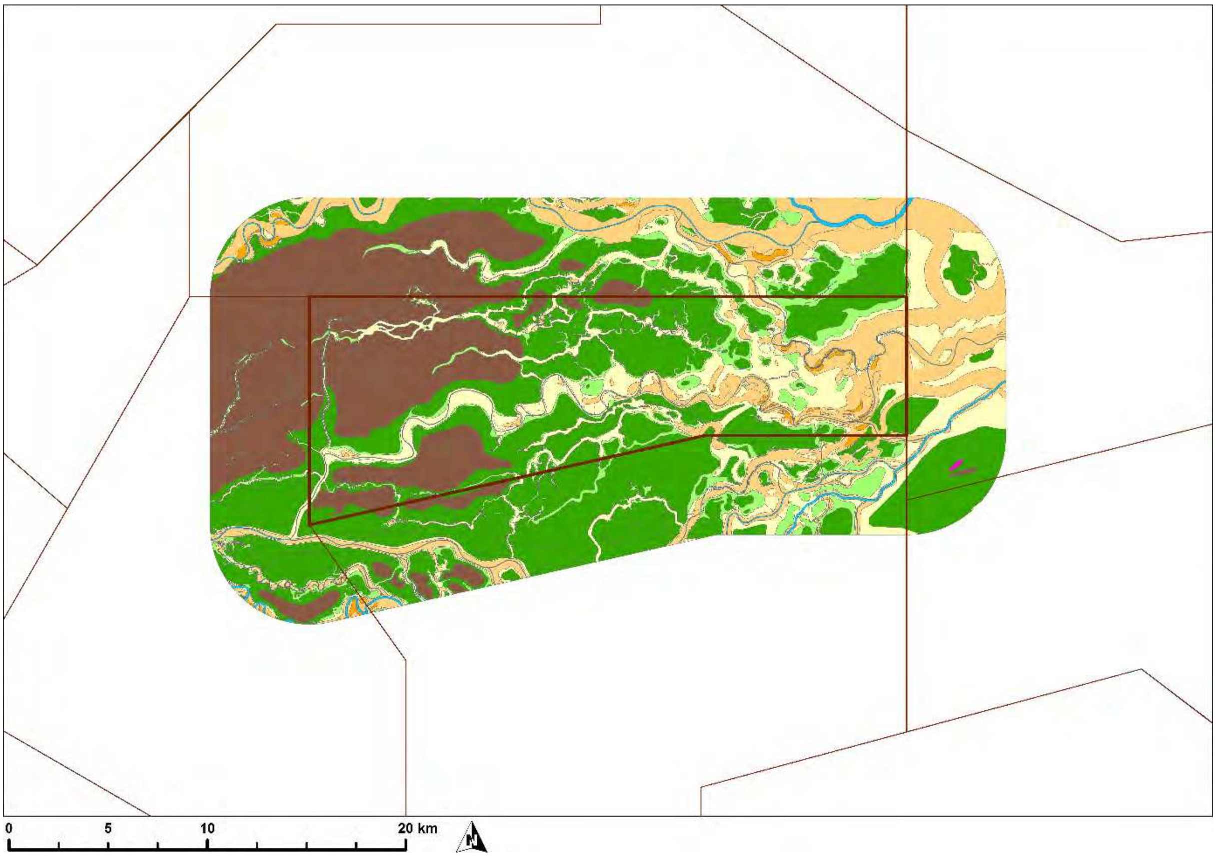


Figure 2.19. Palaeogeography of the 'Linge' region. For legend see Fig 2.5.

2.4.3.4 Western Meuse and Waal (Fig. 2.20)

In this region the Meuse and Waal flow through extensive peatlands, building relatively narrow levees and floodplains compared to the areas west and east from here. There are a number of rivers (re)joining the Waal, such as the Linge (Cohen *et al.* 2012, ID 97) and a river through the Est/Gameren channel belts (Cohen *et al.* 2012, IDs 46, 48), as well as some smaller tributaries that could have been formed as perimarine crevasses and/or peat drainage channels, such as the Giessen channel belt (Cohen *et al.* 2012, 407). There is also a smaller channel connecting the Waal to the Meuse through the Almkerk channel belt that formed early in the Roman Period (Cohen *et al.* 2012, ID 7), although this channel has largely been eroded through the Saint-Elizabeth flood of 1421 and the subsequent formation of the Biesbosch tidal area.

2.4.3.5 Eastern Meuse and Waal (Fig. 2.21)

The Meuse and Waal rivers flow from west to east and have built up broad flood plains in this area. There are a number of connections branching off from the Waal, including the Est/Gameren channel belt (Cohen *et al.* 2012, IDs 46, 48) that rejoins the Waal further west. Some smaller channels connect south to the Meuse, roughly following the route of a main branch of the Waal that flowed in the Meuse in the Late Iron Age (Caesar, *BG* IV, 10; Roymans 2017), and following more recent classical authors possibly connected the Waal to the Meuse in the Early Roman Period as well (Tacitus, *Ann.* II, 6; Plinius, *NH* IV, 101). North of the Waal, between this river and the Linge, a large flood basin is present which is filled with clayey deposits and crossed by several smaller and mostly abandoned channel belts (Gouw and Erkens 2007, 33). A complex of brooks originating in the southern coversands reach the Meuse in this region as well.

2.4.3.6 Southern sands and peatlands (Fig. 2.22)

This area consists of coversands in the south and peatlands between the coversands and the fluvial deposits in the north. Much of this peat has disappeared in more recent periods, either due to human exploitation, due to erosion by flooding or by being covered by younger clay deposits. Some small brooks depart from the coversands and flow north towards the Meuse.

2.4.4 Eastern river area

The eastern river area is subdivided into the regions ‘Veluwe’, ‘eastern Rhine’, ‘eastern Meuse’, ‘Nijmegen-Kleve ridge’ and ‘southeastern sands’.

2.4.4.1 Veluwe (Fig. 2.23)

The Veluwe is a push moraine and is home to the highest elevations in the area covered by the palaeogeographic reconstruction, up to 110 m above NAP[10]. A lower valley is situated between the Utrechtse Heuvelrug and the Veluwe which is filled mostly with coversands. The reconstruction of Vos and De Vries (2013) shows a peatland fill in part of the valley. Since the palaeogeographic reconstruction of the eastern river area uses an automated methodology, these peatlands were not included in the reconstructed map given that they hardly appear on our contemporary soil and geomorphological maps. Although likely erroneous, it was left as it is, since it will not have a large effect on spatial analyses due to its location outside the research area.

[10] *Normaal Amsterdams Peil* – Amsterdam Ordnance Datum.

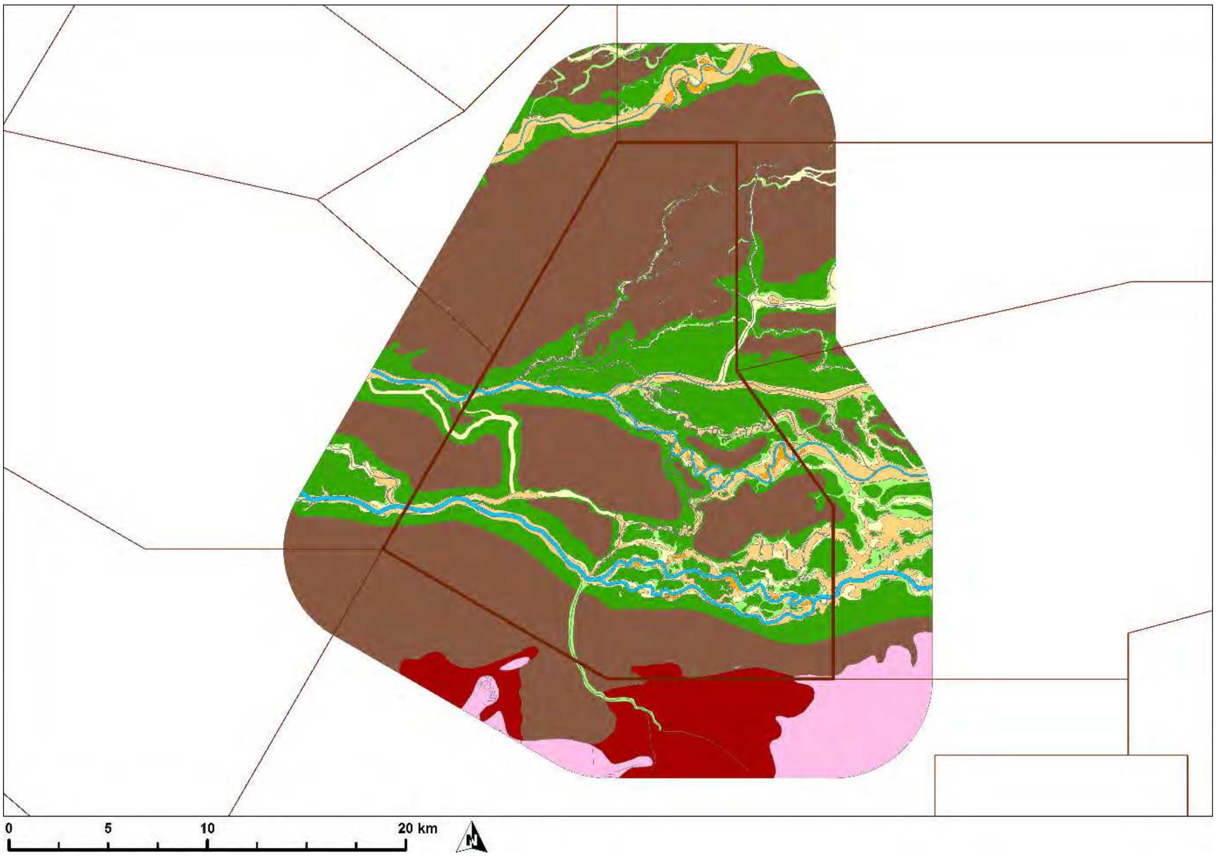


Figure 2.20. Palaeogeography of the 'western Meuse and Waal' region. For legend see Fig 2.5.

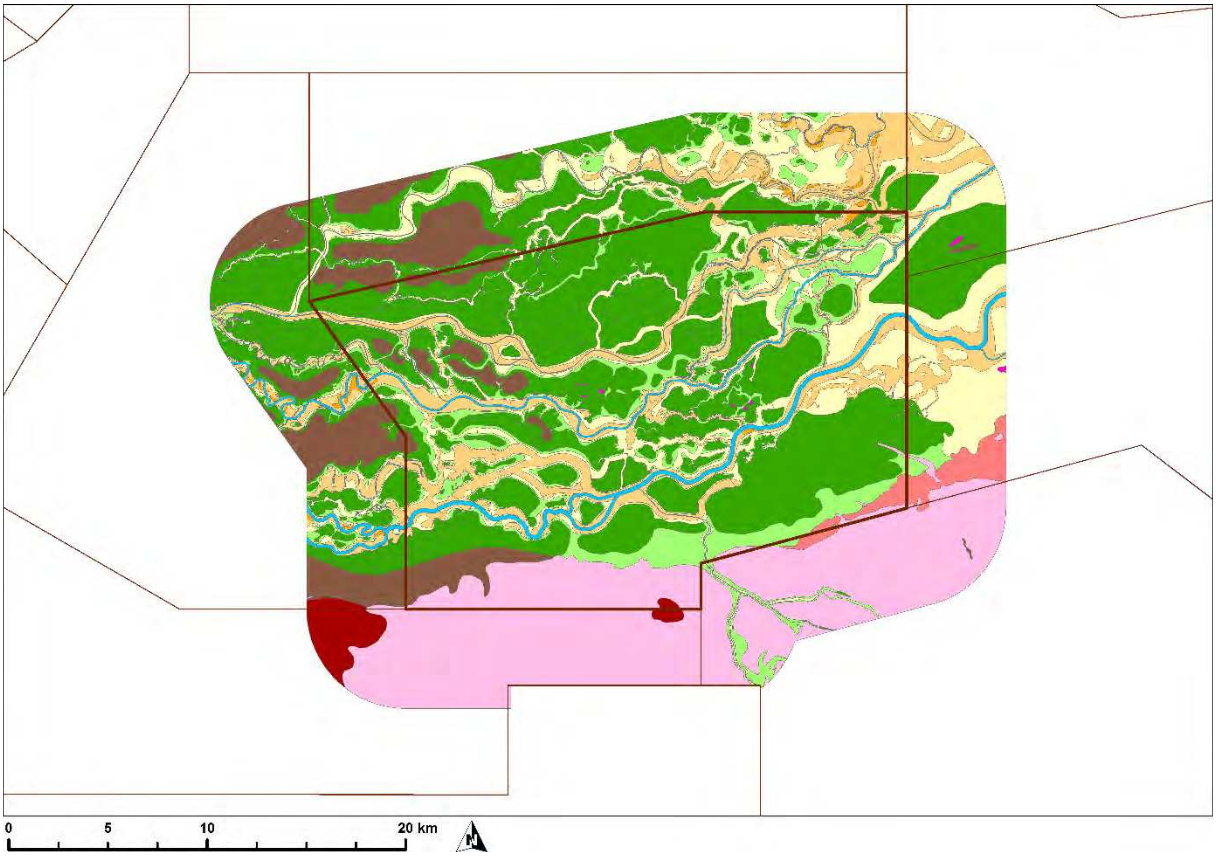


Figure 2.21. Palaeogeography of the 'eastern Meuse and Waal' region. For legend see Fig 2.5.

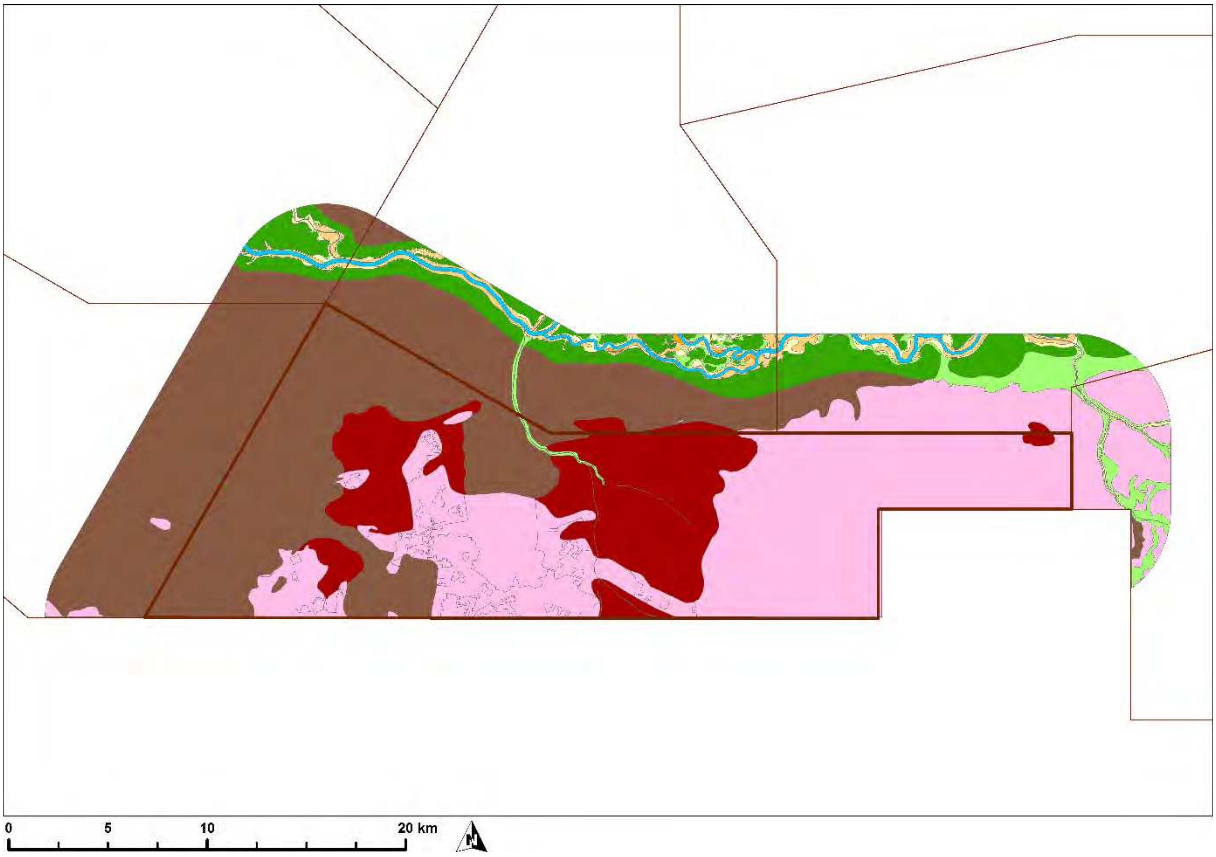


Figure 2.22. Palaeogeography of the 'southern sands and peatlands' region. For legend see Fig 2.5.

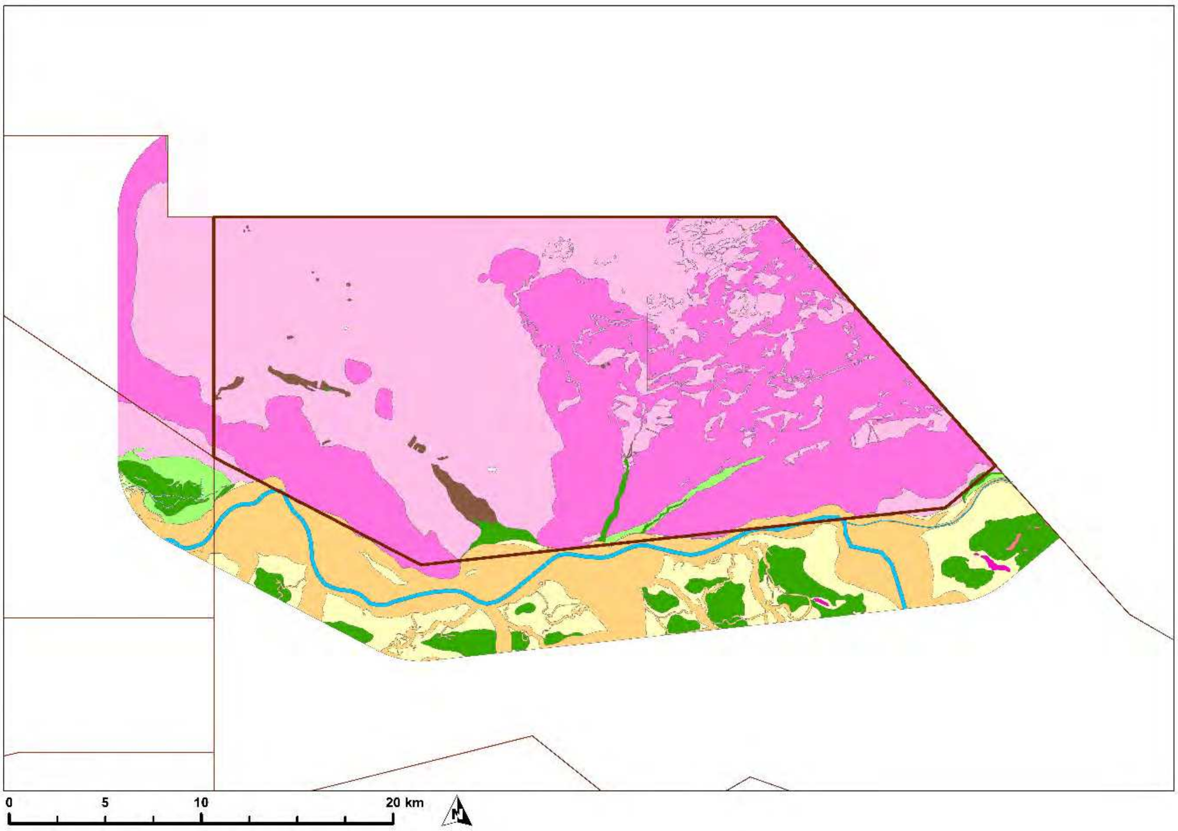


Figure 2.23. Palaeogeography of the 'Veluwe' region. For legend see Fig 2.5.

2.4.4.2 Eastern Rhine (Fig. 2.24)

The 'eastern Rhine' region covers the Rhine delta from the eastern edge of the research area until the Utrechtse Heuvelrug. Here the Rhine is characterised by broad levees as well as levees and channel belts of abandoned river courses, with relatively small lower floodplains in between. In the east, the Waal departs from the Rhine to follow a parallel yet more southern course, towards the Meuse estuary. The exact point where this split occurred is debated: the significant amount of post-Roman erosion leaves more than one possibility. The current reconstruction follows that of Vos and De Vries (2013). The Linge, which was a larger branch of the Waal river prior to the Roman Period, departs from the Waal to rejoin it later in the western peatlands.

2.4.4.3 Eastern Meuse (Fig. 2.25)

The Meuse has formed a number of fluvial terraces in the 'eastern Meuse' region between the coversands in the southwest and the higher Pleistocene sands in the northeast. The current terrace crossing, where the rivers shift from erosion to sedimentation, is located near Rees (Germany). During the Roman Period this was only a few kilometres downstream (Berendsen and Stouthamer 2001, 72). In the upstream part of the 'eastern Meuse' region this leaves very little room for the river to migrate laterally. Downstream the Meuse has more space available where it can aggradate, resulting in broad levees along its current course and a number of abandoned courses. There are some smaller river dunes in the floodplain north of the Meuse, which form very local elevated parts of the landscape.

2.4.4.4 Nijmegen-Kleve ridge (Fig. 2.26)

The Nijmegen-Kleve ridge is a push moraine that is part of a larger complex of push moraines known as the 'Lower Rhine ridge' (Siebertz 1984), extending into Germany between the Rhine and Niers rivers. The Meuse and to a lesser extent the Rhine have built up fluvial terraces on the sides of the moraine.

2.4.4.5 Southeastern sands (Fig. 2.27)

The 'southeastern sands' region consists largely of coversands interspersed by narrow brook valleys that can have a filling of clay or peat. Geomorphologically this area has undergone very little changes since the end of the Pleistocene. Further to the south a larger peatland has formed on the Pleistocene coversands, known as the Peel, but this area falls outside the boundaries of the palaeogeographic reconstruction.

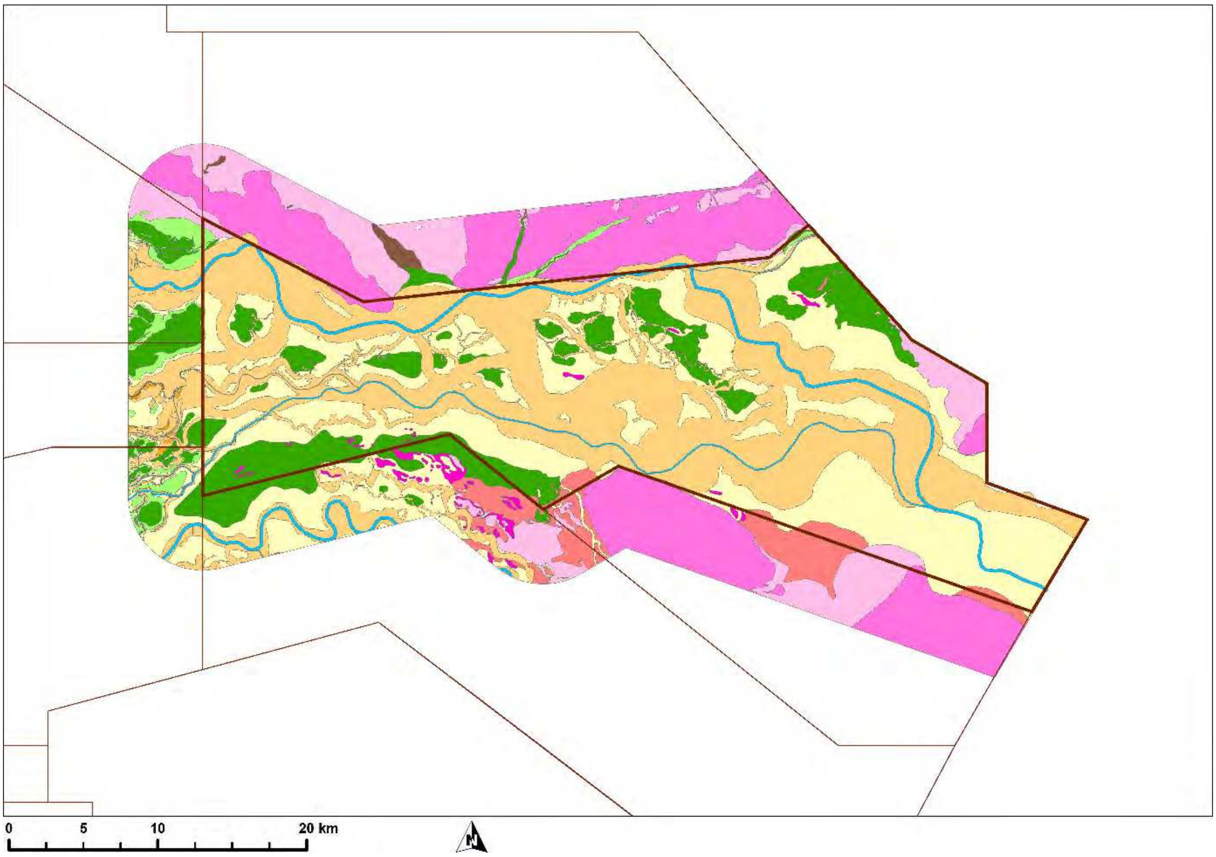


Figure 2.24. Palaeogeography of the 'eastern Rhine' region. For legend see Fig 2.5.

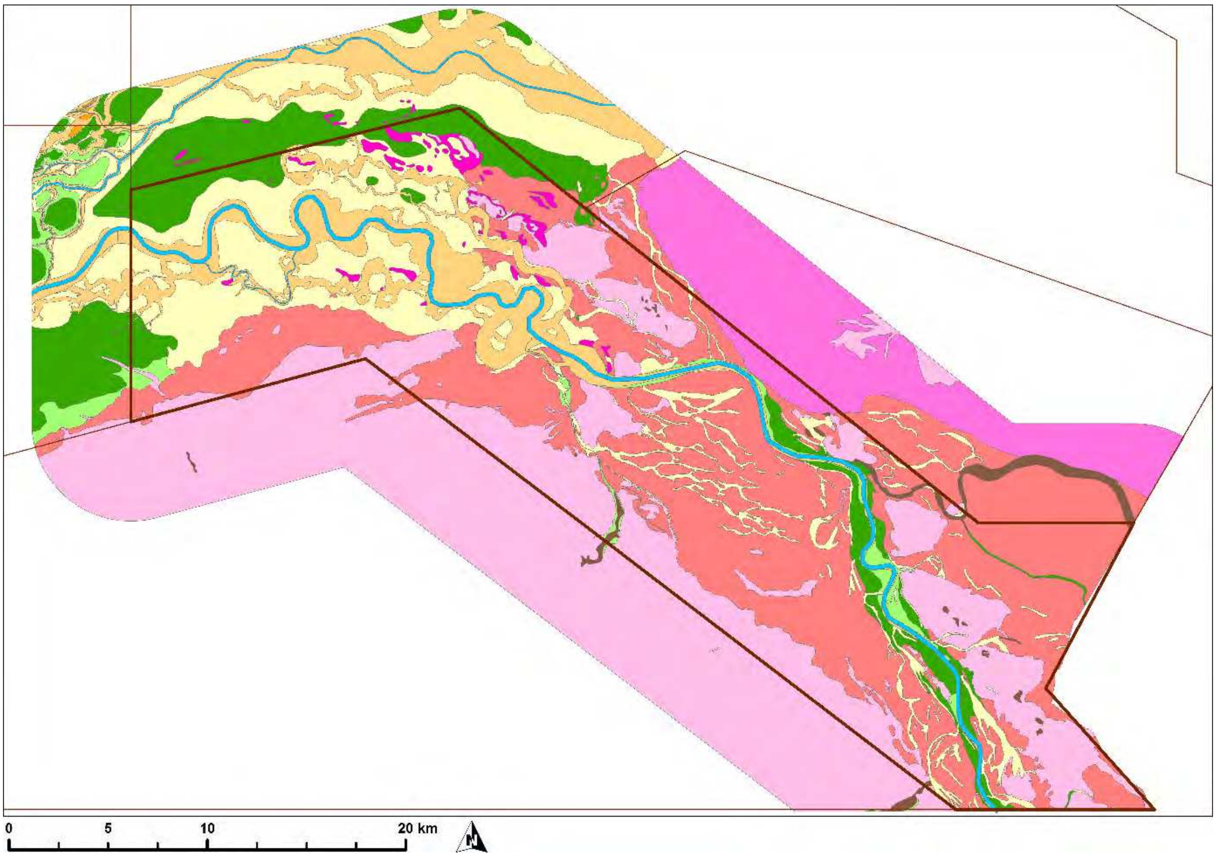


Figure 2.25. Palaeogeography of the 'eastern Meuse' region. For legend see Fig 2.5.

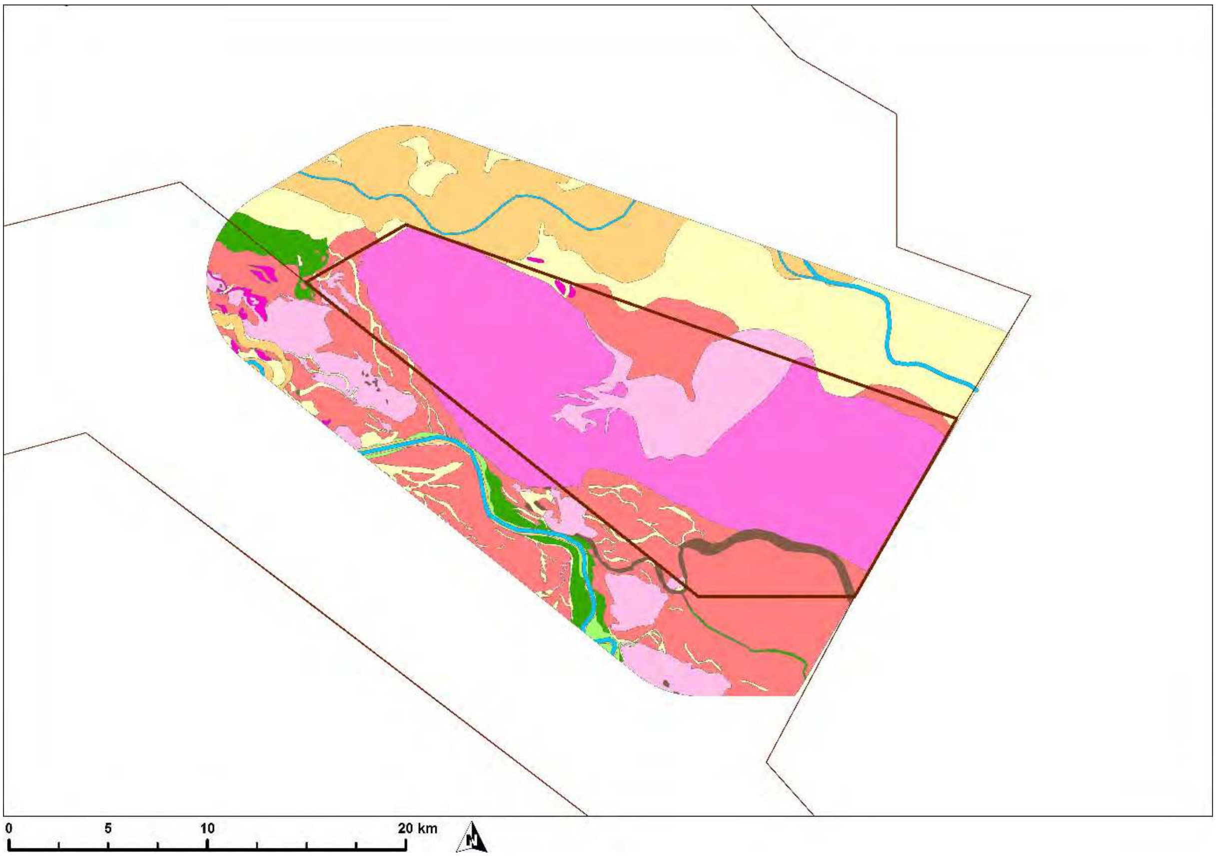


Figure 2.26. Palaeogeography of the 'Nijmegen-Kleve ridge' region. For legend see Fig 2.5.

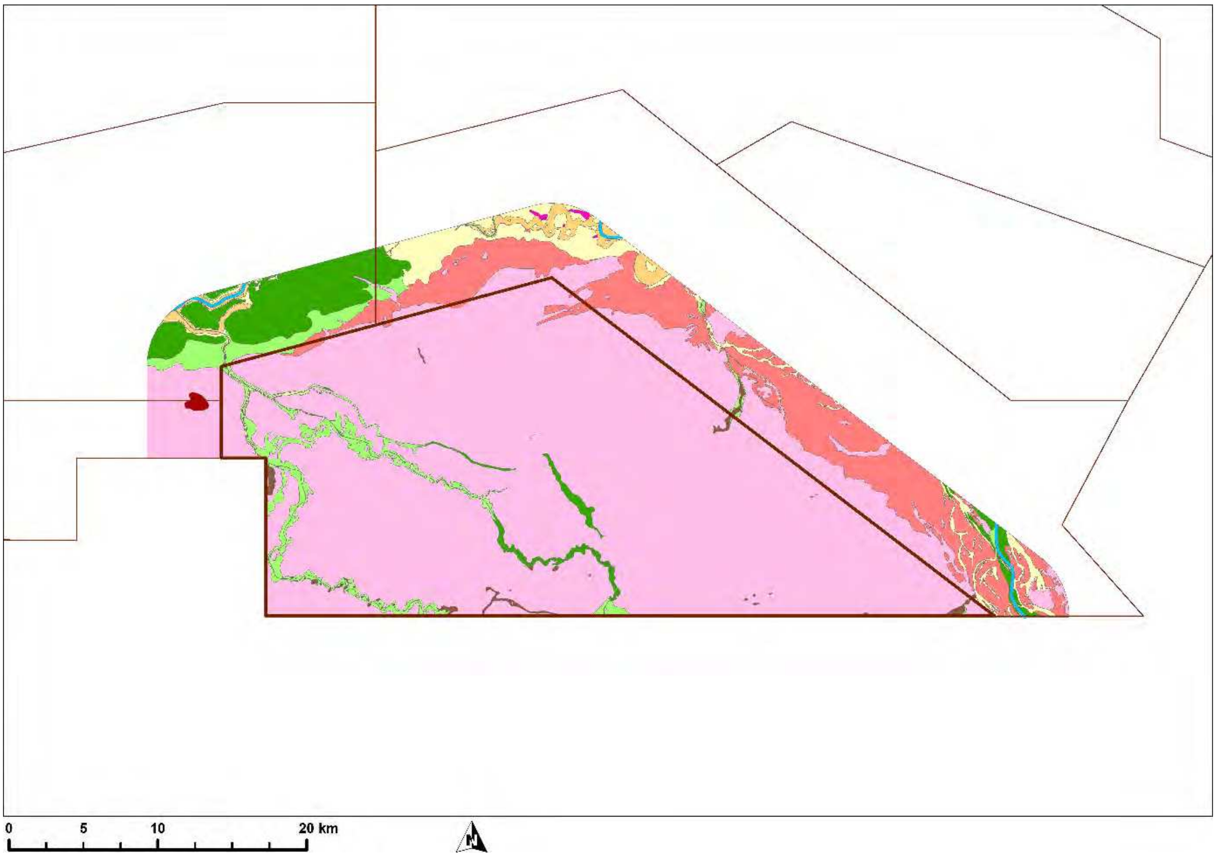


Figure 2.27. Palaeogeography of the 'southeastern sands' region. For legend see Fig 2.5.

2.5 Uncertainty in palaeogeographic mapping

Uncertainty is an inherent aspect of palaeogeographic mapping as it is literally mapping the landscape in a past that is often no longer visible in the present. Earlier palaeogeographic mapping often left uncertainty implicit. Mostly the issue is not acknowledged at all, and sometimes only indirectly, approaching the issue through aspects such as the availability and scale of source data, sampling data density or a limited intended scale for user applications. Among the more notable palaeogeographic reconstructions, Zagwijn (1986, 33–42) approaches uncertainty in his reconstructions by generally pointing out blank areas in the sources (mostly those as a result of erosion) and stating more explicitly but still in general terms when assumptions have been made. Vos and De Vries (2013) follow his line, providing an overview of the limitation of the sources used and pointing out some blank spots in the palaeogeographic reconstructions (Vos 2015, 58). Van Dinter (2013) made a substantial improvement by actually embedding the areas of uncertainty in her palaeogeographic map (Fig. 2.28). The downside of this methodology is that the uncertainty assigned is binary (the reconstruction of an area is either certain or uncertain) and the source of the uncertainty is unknown.

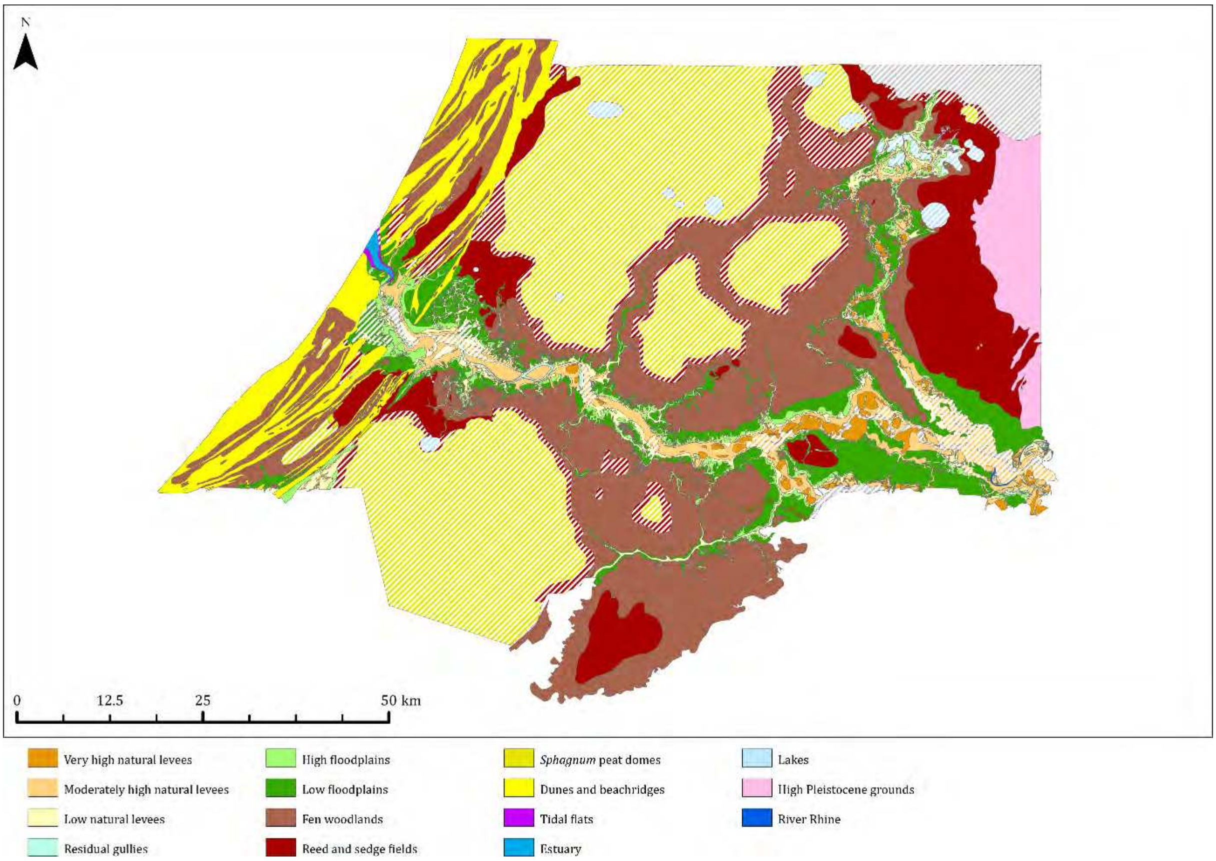


Figure 2.28. Explicit binary uncertainty (uncertain areas shown through hatching) in the palaeogeographic reconstruction of Van Dinter (2013).

In order to better understand the reliability of a palaeogeographic map, the aim of this section is to make uncertainty an even more explicit part of the palaeogeographic mapping of the Dutch part of the Roman *limes* and to shed more light on the sources of uncertainties. This will be done by presenting a case study of the area around the Kromme Rijn and Hollandse IJssel near the modern city of Utrecht (Fig. 2.29), in order to present the various sources of uncertainty, and from there work towards a tentative uncertainty map for the palaeogeographic reconstruction of the Dutch river area during the Roman Period.

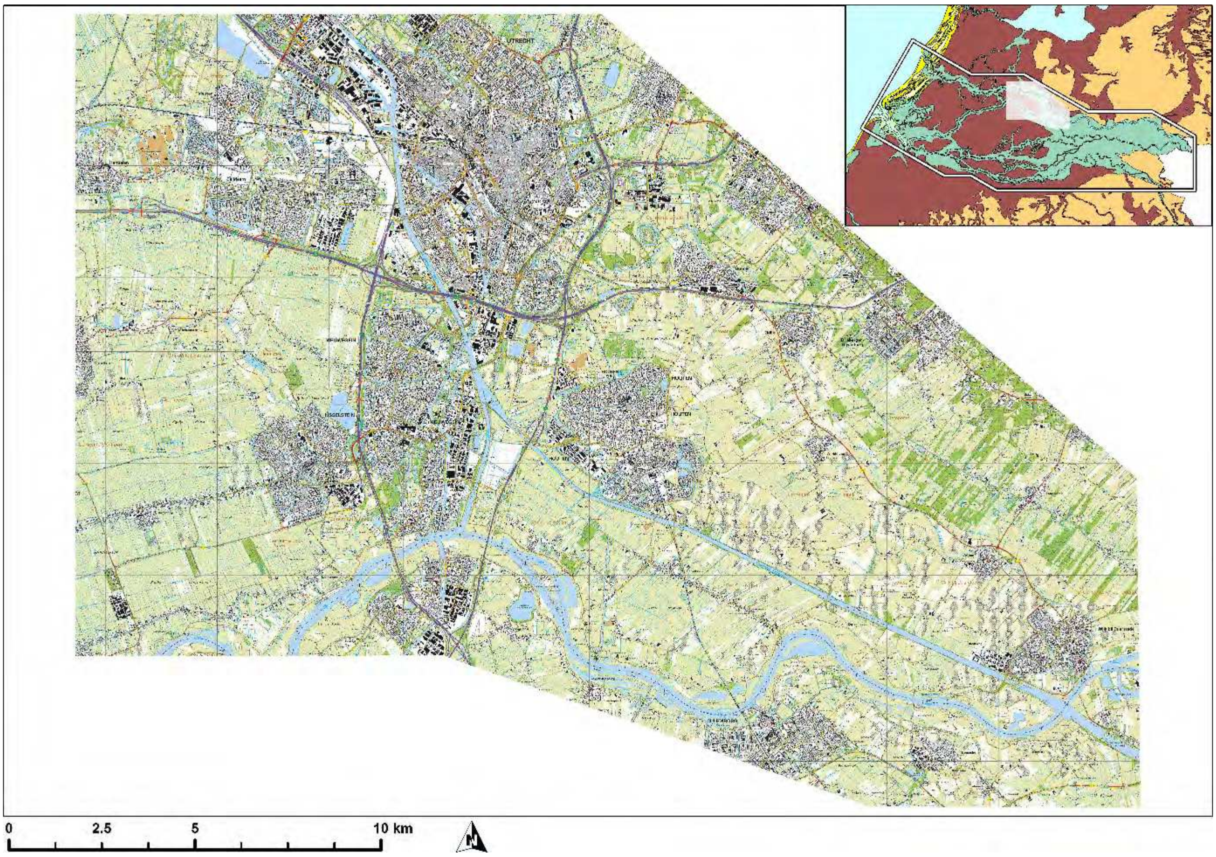


Figure 2.29. Modern topography of the Kromme Rijn-Hollandse IJssel case study area near the modern city of Utrecht, and its location in the research area.

2.5.1 Sources of uncertainty

Erosion is one of the primary sources of uncertainty in palaeogeographic reconstructions, and one of the primary causes of erosion in the Dutch river area is fluvial activity. After the Roman Period, rivers were still able to migrate and change their course through avulsion and bury or erode fluvial deposits that were present before until the construction of dikes in the Medieval period. The potential extent of post-Roman erosion through fluvial activity can be established quite well thanks to the available data on channel belt palaeogeography (Cohen *et al.* 2012), by filtering the dataset for channel belts that were active after the Roman Period (Fig. 2.30). However, it must be noted that older fluvial deposits can persist in active channel belts. For example, Cohen *et al.* (2014) have mapped the age of individual elements within the dikes of the current rivers, showing the preservation of small remnants of fluvial deposits in active channel belts going back to Roman times and even earlier.

A problem in the palaeogeographic reconstruction of the sandy areas of the Netherlands is the presence of post-Roman drift sand deposits, mainly formed after AD 950 (Castel *et al.* 1989). Drift sand activity is often found to be related to the expansion of 'plaggen' arable farming in the Late Medieval period (Koster *et al.* 1993, 248). The majority of drift sand formations has stabilised since reforestation in the 19th century. Although some drift sand deposits can be mapped by hand using LIDAR elevation data based on their characteristic chaotic relief (Koster *et al.* 1993, 248), this likely does not cover all drift sand deposits and would require more manual interpretation, adding to the uncertainty expected from drift sand activity in the first place. Therefore, a standardised methodology was applied to filter for likely drift sand landforms, overlaying sandy landforms extracted from the geomorphological maps (with the exception of the coastal dunes) with '*vaaggronden*' (arenosols) extracted from the soil map (Fig. 2.31). This is based on the assumption that due to their young age drift sand deposits will have little to no soil formation, as opposed to coversand deposits which have mostly been stable long enough for podzol formation. However, even though drift sand activity may pose a problem for a reconstruction of the natural palaeogeography, it must be said that it is a marginal problem for Roman settlement, since hardly any settlements are known to exist in these areas.

The extent and nature of the peat cover is always problematic in palaeogeographic reconstructions. The initial source for peat reconstruction is often the soil map, to identify areas where peat is still present today. This overview is very incomplete however, as large areas of peat have been buried by younger fluvial depositions, resulting in their disappearance from the soil map (De Bont 2008, 70), or have disappeared due to medieval peat reclamation. Until recently there was no overview of medieval peat reclamations on a national scale (De Bont 2008, 51), making it difficult to map this source of uncertainty. To some extent peat reclamations could be be recognised on 19th century topographic maps (Fig. 2.32), in many cases due to their consistent dimensions known as *cope* exploitations, although this type forms only a fraction of medieval peat reclamations (De Bont 2008, 44). The first nation-wide overview of peat reclamations was published in 2016 through research funded by the RCE (Bekius and Kooiman 2016).

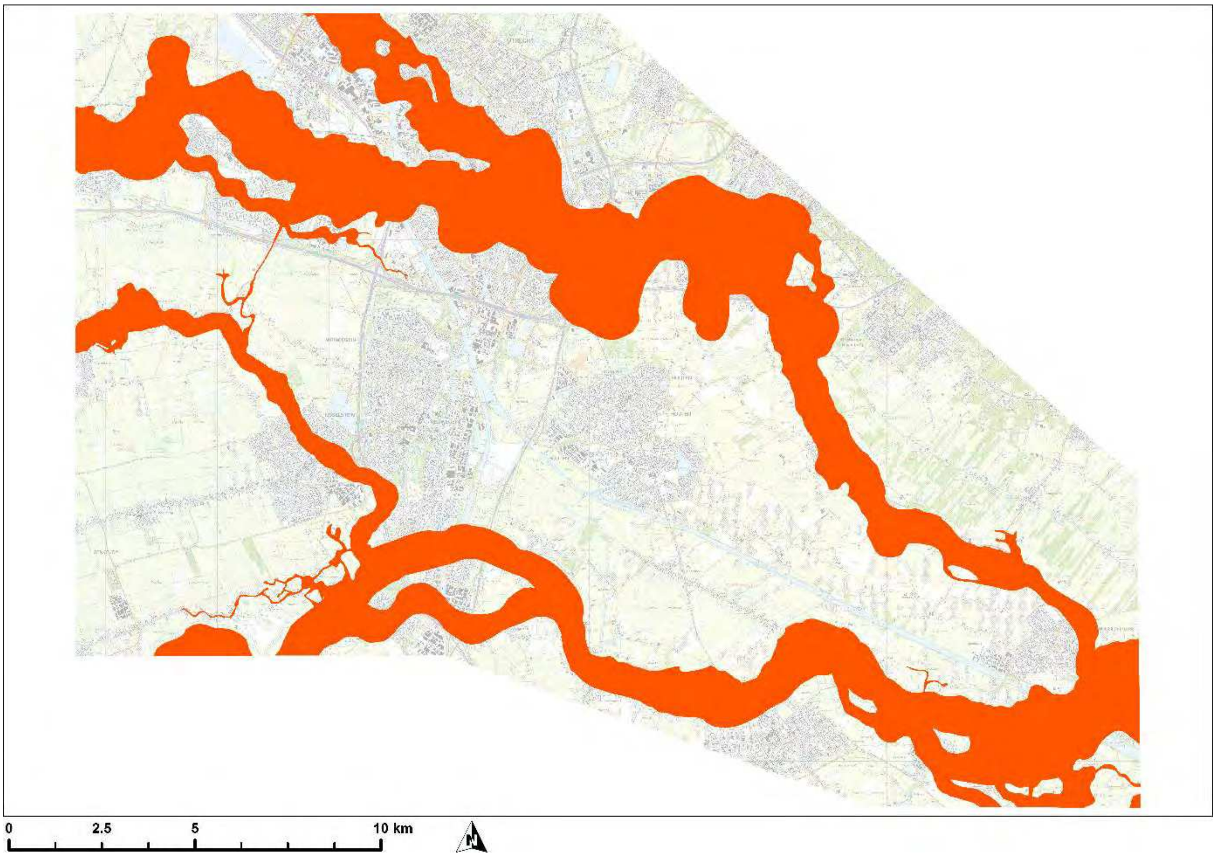


Figure 2.30. Post-Roman fluvial activity (from Cohen et al. *2012) in the case study area.*

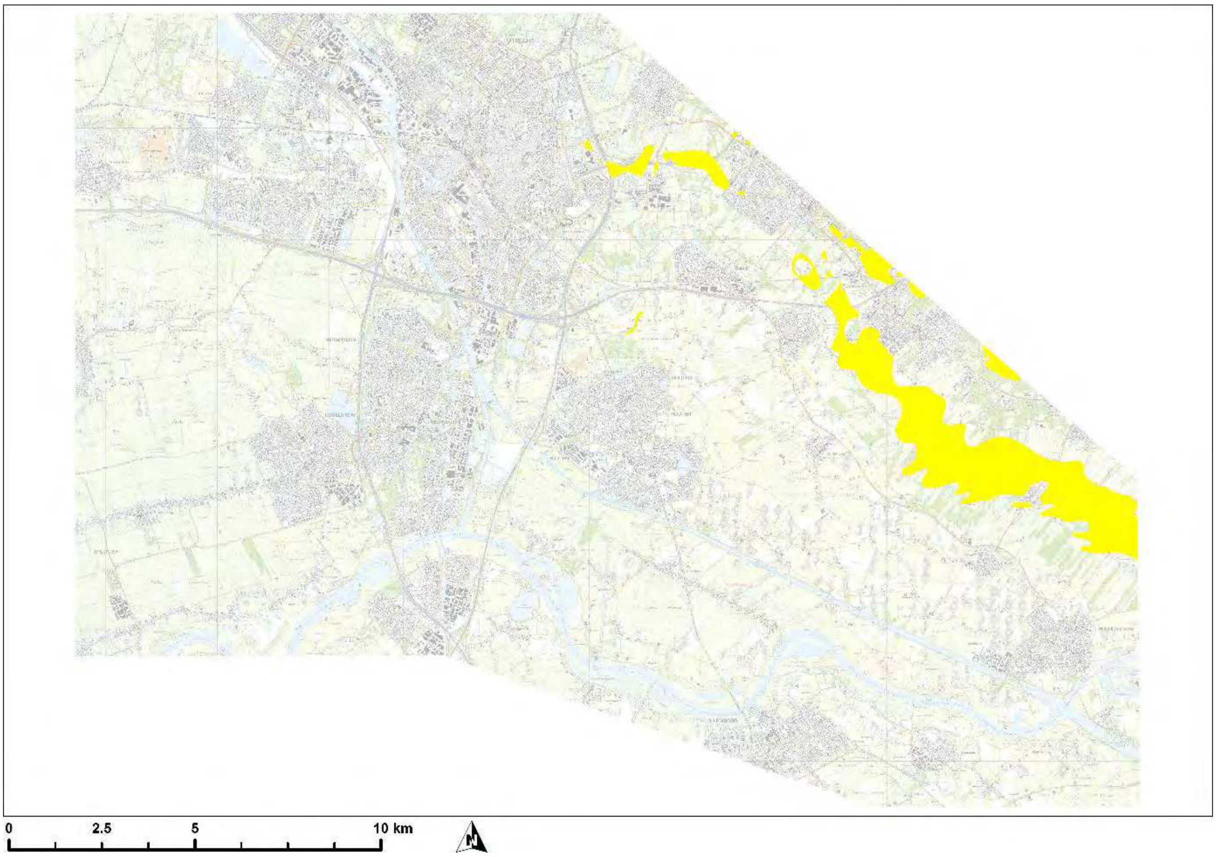


Figure 2.31. Areas recognised as drift sand deposits in the case study area, based on the combination of sandy landforms from the geomorphological map with arenosols from the soil map.

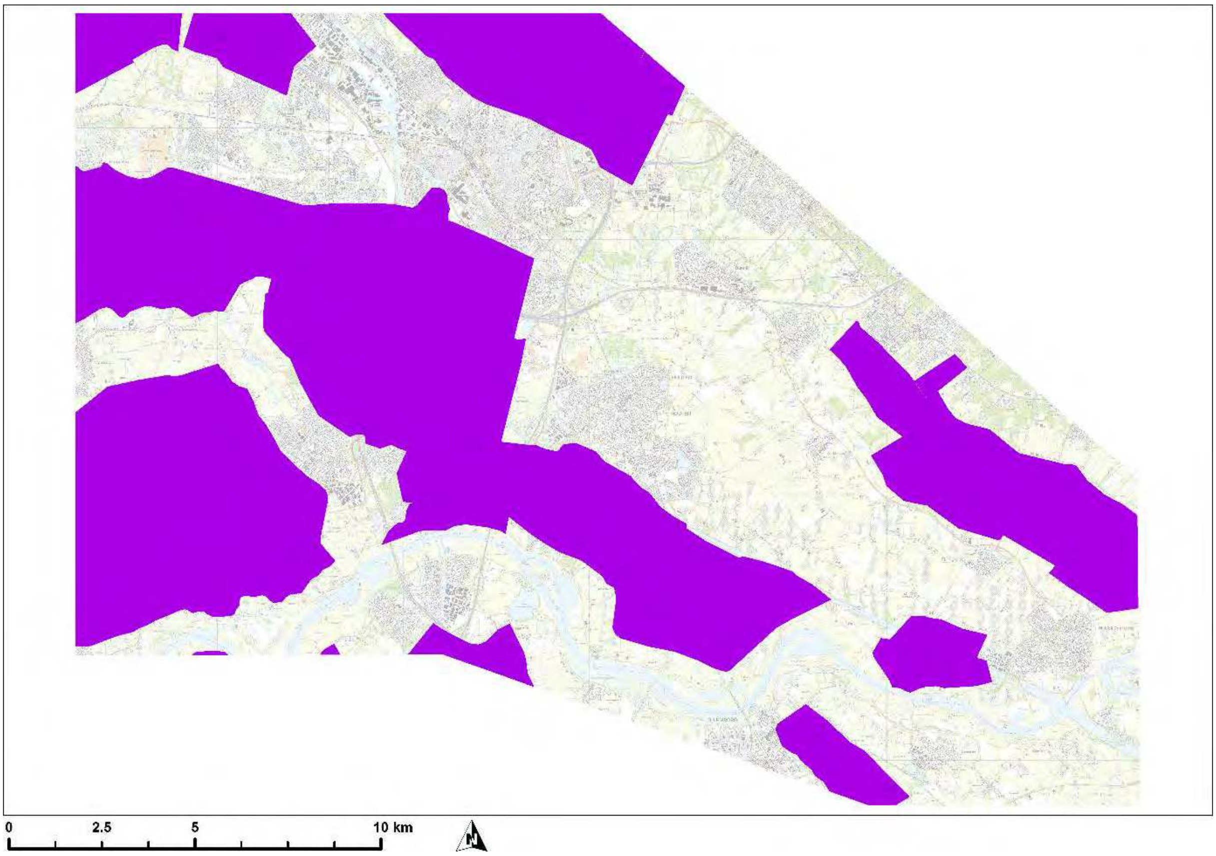


Figure 2.32. Reconstruction of medieval peat reclamation in the case study area based on 19th century topographic maps.

A primary and clearly recognisable source of uncertainty is urban development. This is reflected in a number of sources, such as the geomorphological maps and the soil maps, where they are included as a separate legend unit and thus present nothing about the geomorphology or soil on which they are located. Urban development is also a disturbing factor in the LIDAR elevation data, as the land in urban areas is often raised and/or levelled and of course obscured by buildings, infrastructure etc. These sources of uncertainty were mapped by extracting the legend units for urban areas from the geomorphological maps and soil maps, and manually adding the additional urban cover that is visibly obscuring the LIDAR elevation data. Additional (primarily non-urban) anthropogenic elements that are obscuring factors in the source data are quarries, excavated areas, dikes, embankments, dwelling mounds and levelled areas. These are all recognised as separate legend units in the geomorphological maps and soil maps and can be directly extracted from them (Fig. 2.33).

Modern surface water is a source of uncertainty which is rather difficult to isolate, as it is also featured in other categories such as post-Roman fluvial activity (for modern rivers) and medieval peat reclamations (ranging from small ditches up to lakes formed by peat excavations). However, it is featured as a separate legend unit in geomorphological maps and soil maps and undeniably obscures Roman landscape reconstruction based on LIDAR elevation data, so for that reason modern surface water was extracted from the geomorphological maps to serve as a distinct source of uncertainty (Fig. 2.34).

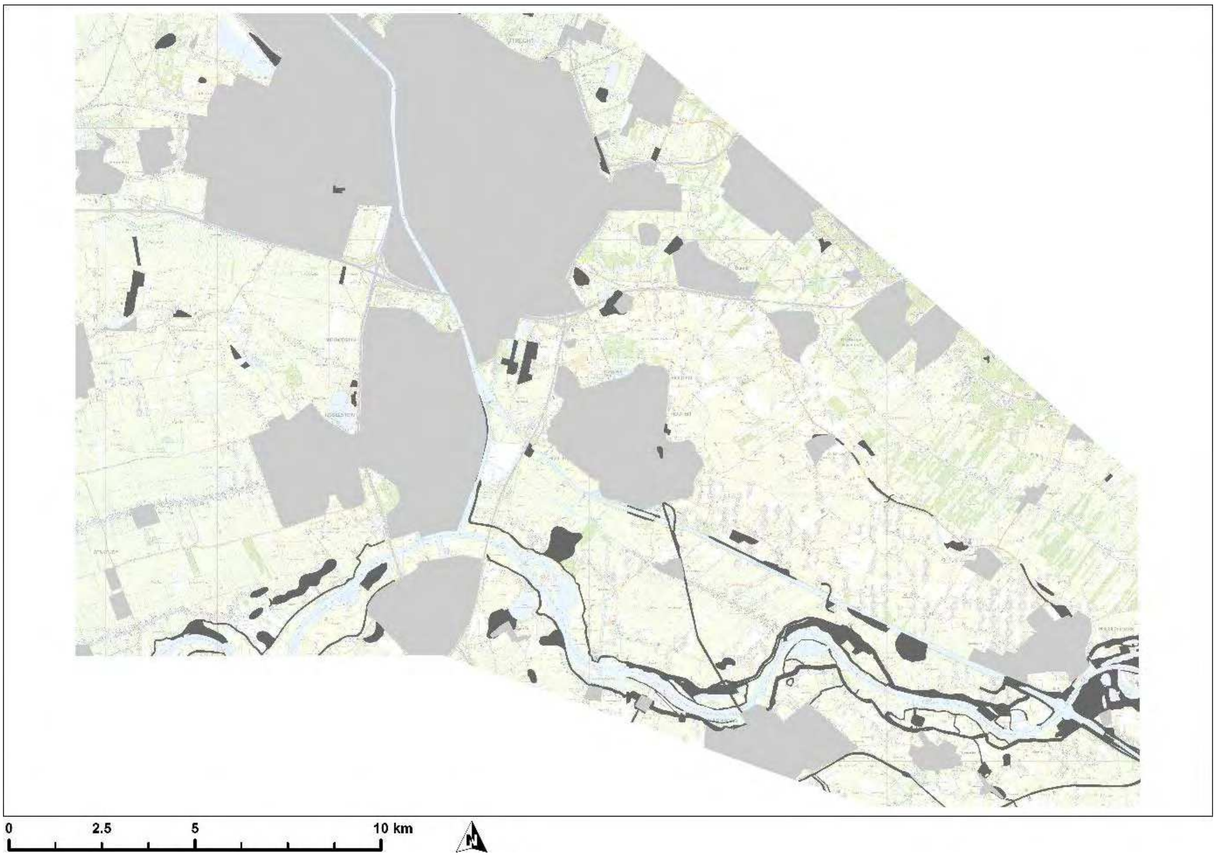


Figure 2.33. Urban development (light grey) and other anthropogenic elements (dark grey) in the case study area.

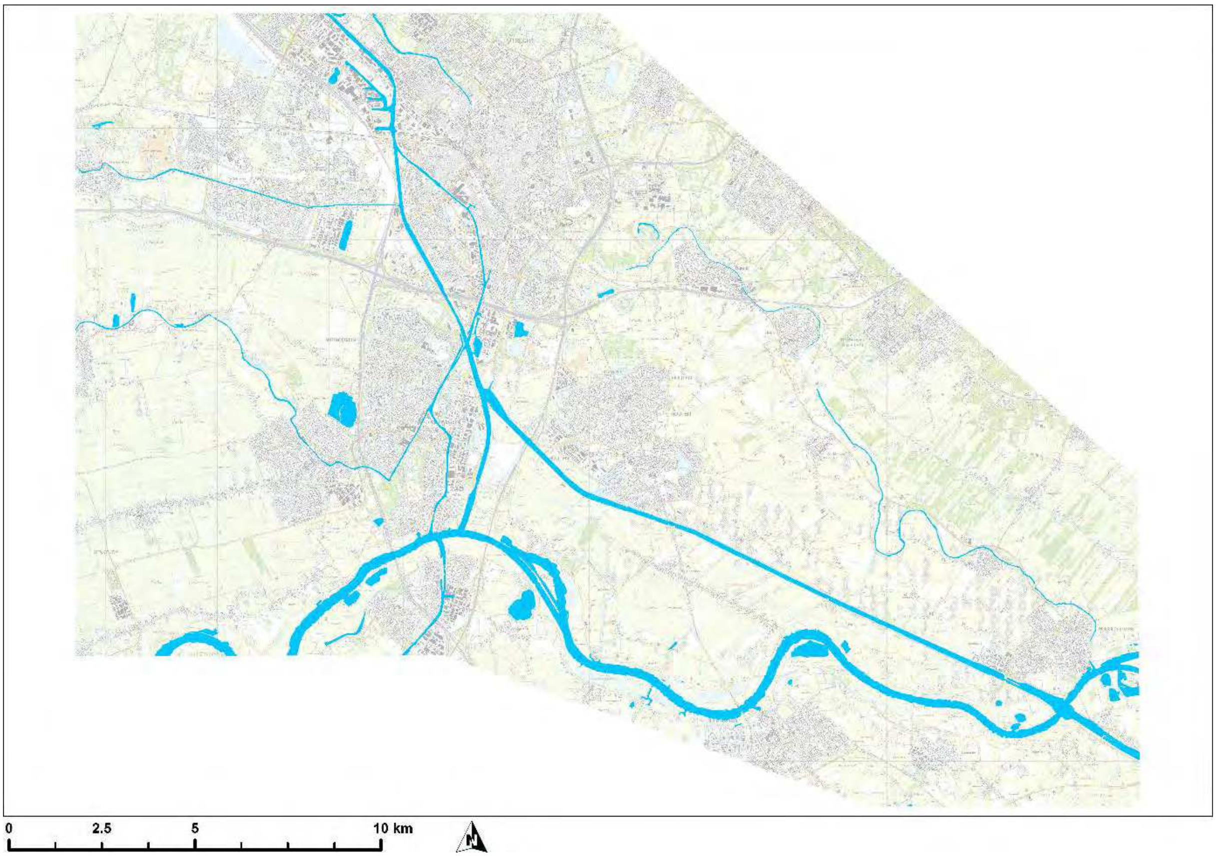


Figure 2.34. Modern surface water in the case study area.

A point of discussion related to the certainty of palaeogeographic mapping is the availability of source datasets, and the spatial resolution of them. It might be argued that this influences the quality of the palaeogeographic reconstruction, as the availability and scale of soil data, geomorphological data and palaeogeographic data can vary widely across local sources. However, higher scales do not necessarily mean a higher quality palaeogeography, as it is often based on sources with scales of a lower resolution. A good example in the case study area is the palaeogeographic map series of the municipality of Wijk bij Duurstede (Klerks *et al.* 2012), which is presented at a scale of 1:10,000 but is based for large parts on sources of a scale up to 1:50,000. Furthermore, there are actually sources that are consistently available at a 1:50,000 scale, namely the geomorphological maps and the soil maps, as well as even more detailed LIDAR-derived elevation data. Given that the inadequacies in these datasets are already covered by the sources of uncertainty outlined earlier, and the fact that the palaeogeographic reconstruction in this study is intended to be at a 1:50,000 scale, it is not necessary to further include the availability and scale of other source datasets in constructing uncertainty maps.

The sources of uncertainty can be summed to create a tentative 'uncertainty map' for the palaeogeographic reconstruction of the case study area during the Middle Roman Period (Fig. 2.35). This provides a quick overview of areas that are relatively certain in their palaeogeographic reconstruction and areas that are relatively uncertain, whereas the individual elements can be consulted to see where the uncertainty originates. In this exercise each source of uncertainty is given an equal weight, but of course this does not necessarily have to be the case. More weight can be given for instance to post-Roman fluvial activity (potentially eroding the entire Roman landscape) as opposed to urban development (which sometimes only obscures the Roman landscape). Using the same methodology, the uncertainty map can be expanded over the rest of the research area (Fig. 2.36). Potentially new sources of uncertainty can be introduced when they are identified, such as post-Roman coastal erosion or plaggen soils in the southern Netherlands.

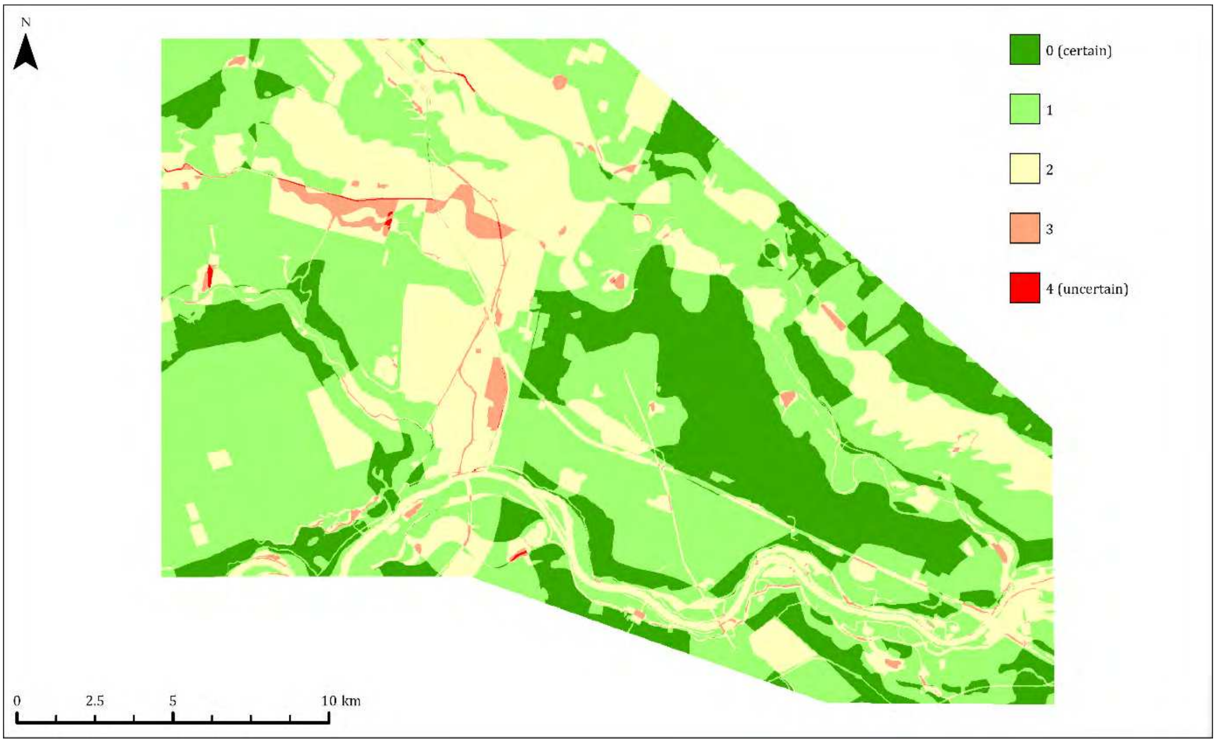


Figure 2.35. Uncertainty map related to the palaeogeographic reconstruction of the case study area.

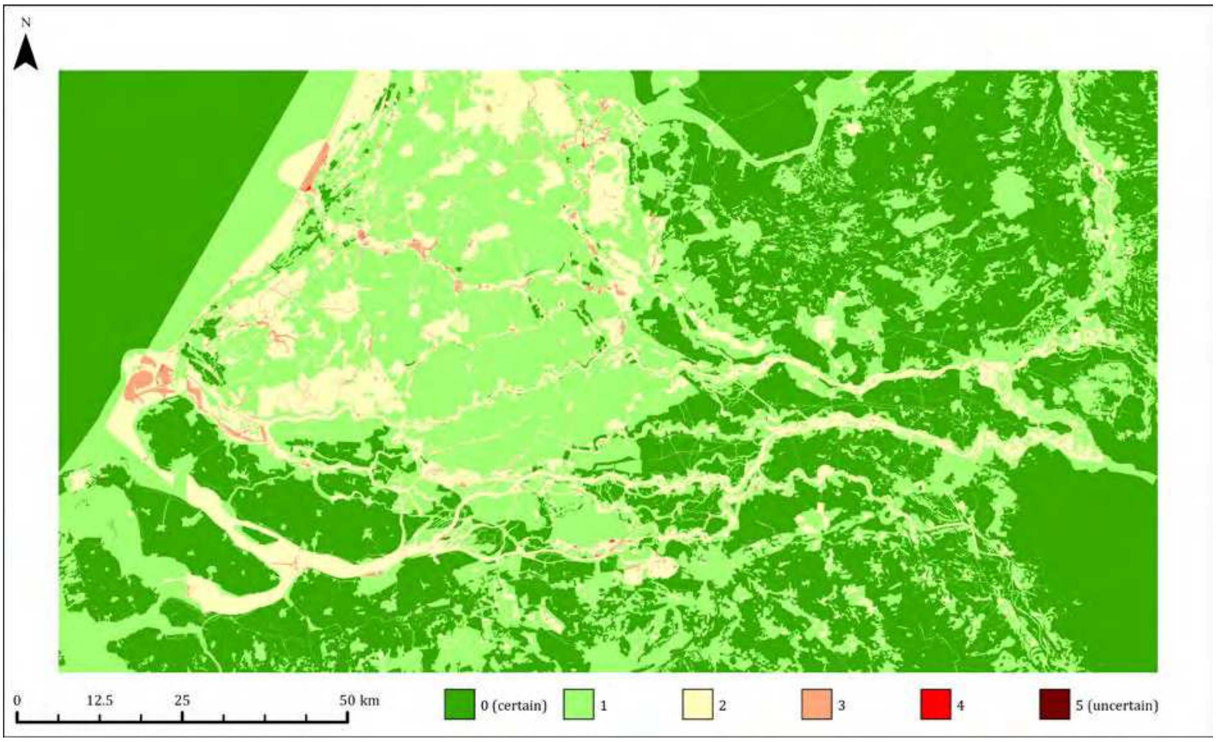


Figure 2.36. Uncertainty map related to the palaeogeographic reconstruction of the research area.

2.6 Discussion

At the start of the project, a reconstruction of the natural palaeogeography of the Dutch *limes* area, suitable for detailed quantitative analyses, was not yet available. The only palaeogeographic reconstructions available for the entire research area (i.e. Vos and De Vries 2013) are too coarse for such approaches. Projects with detailed palaeogeographic reconstructions have been undertaken in the past for smaller areas, examples being the project on the western Netherlands in the first millennium (Bazelmans *et al.* 2002; Dijkstra 2011) and the project on the Roman *limes* in the Old Rhine area (Kooistra *et al.* 2013; Van Dinter 2013; Van Dinter *et al.* 2014). The work done in the latter project has been incorporated in this study, and the methodology for reconstruction has been applied to extend the map to cover the entire research area.

Furthermore, even though detailed palaeogeographic reconstructions were available for some regions of the Dutch *limes* area (e.g. Van Dinter 2013), the full analytical potential of such reconstructions is yet to be explored. So far applications remain mostly on the level of regional analysis, qualitative site location analysis and exploratory quantitative analysis, while a detailed regional palaeogeographic reconstruction lends itself to more detailed quantitative analysis in the same way that data on the modern environment is often used in computational archaeological research. Such applications of palaeogeographic reconstructions are fairly new but have already been shown in local case studies, for instance concerning least-cost path modelling (Verhagen *et al.* 2013a; Groenhuijzen and Verhagen 2015). The palaeogeographic map of the Dutch *limes* area during the Roman Period is constructed with the intention of using it for spatial analysis, including path modelling, network construction, site location analysis and agricultural production models, part of which will be elaborated upon in the following chapters.

An addition that was added to this work that was underappreciated so far in palaeogeographic research is the explicit acknowledgement of uncertainty. In past palaeogeographic mapping project uncertainty was obviously present due to the inherent nature of the processes that form, shape and erode the landscape, yet the uncertainty was not explicitly acknowledged but only treated in more general observations. Van Dinter (2013) made steps by defining uncertainty in a binary format, so that it is clear which areas are certain and which ones are uncertain in their reconstruction. In this methodology however, these areas are derived from the expert judgement of the mapper and it is unclear on what grounds the uncertainty is based. In the palaeogeographic reconstruction of the Dutch *limes* area in this project, it is aimed to make uncertainty even more explicit by building uncertainty maps and including the various sources of uncertainty. It is apparent in Fig. 2.36 that uncertainty is much greater in the fluvial elements of the landscape than outside them. This can be attributed to the dynamic nature of the fluvial landscape in comparison to the sandy landscapes. Rivers erode and deposit new material over short periods of time, while the sandy areas, with the exception of the drift sands and the younger dunes, have been relatively stable for the largest part of the Holocene. When considering the use of palaeogeographic maps for spatial analyses and modelling it is important to know where uncertainty resides, as they can influence the outcome of the research. For example, when modelling least-cost paths through a fluvial landscape, the presence or absence of relatively traversable levees or relatively impassable peatlands makes a big difference. An example of such a case will be shown in Chapter 5, section 5.4.3.

Simultaneously with the work being done in this project on reconstructing the natural palaeogeography of the Dutch *limes* area, another map series was developed in the project 'Dark Ages of the Lowlands' at Utrecht University that focussed on the first millennium AD (Pierik *et al.* 2016; 2017; Pierik 2017). Pierik *et al.* (2017) used a different methodology for constructing the palaeogeographic map of the Rhine-Meuse delta. In this methodology, natural levees were identified on the basis of a lithology of silty clay, clay loam or loam, derived from the Utrecht borehole database. Then, LIDAR elevation data was used to manually digitize levee and floodplain delineation from the borehole queries and from the existing palaeographic dataset of channel belts (Cohen *et al.* 2012). The identified levees were dated using the extensive database of ^{14}C-dates associated with the channel belt palaeogeography. The resulting dataset can then be used to extract palaeogeographic time slices. A similar methodology was used in the mapping of the coastal plain palaeogeography (Pierik *et al.* 2016). For the natural levees, a palaeo-elevation model was constructed using the borehole data, which was subsequently converted to relative elevation normalised to the floodplain gradient using groundwater-level reconstructions (Koster *et al.* 2017). The resulting palaeogeographic reconstructions were used to model route networks (Van Lanen and Pierik in press) and habitation patterns in relation to relative elevation (Pierik and Van Lanen in press) for three time slices in the first millennium AD, one of which concerns a reconstruction of AD 100.

Despite using a different methodology, the palaeogeographic reconstruction presented in this chapter and the one developed by Pierik *et al*. (2016; 2017) are fairly similar. This is likely due to being reliant on many of the same datasets, such as the channel belt palaeogeography (Cohen *et al.* 2012) and LIDAR elevation data. One valuable addition is the construction of a map of palaeo-elevation, which could be used to model habitation patterns in relation to elevation. Such an approach would not have been possible using the map constructed in this project. On the other hand, the more procedural construction of palaeogeographic data applied by Pierik *et al.* 2017 may make it more difficult to incorporate research from local sources, such as data derived from archaeological excavations, which for example have been shown to be very valuable to the understanding of Roman fort locations (Van Dinter 2013).

For future research, a beneficial development would be to better merge the methodology with automated procedures using a large dataset of boreholes and ^{14}C-dates developed by Pierik *et al.* (2016; 2017) with local source data such as what has been applied in the methodology in this study. In combination with the available ^{14}C-dates, the integration with available archaeological information would allow for an even better control of the dating of the mapped palaeogeographic elements. Furthermore, the integration of archaeological information might even lead to new interpretations that are difficult to achieve only on the basis of the available borehole data due to fluvial erosion processes, such as the hypothesised connection between the Meuse and Waal near Kessel in the Late Iron Age (Roymans 2017).

3 The archaeological site dataset

3.1 Introduction

One of the most vital components for a regional study is a reliable archaeological site dataset upon which the analyses and interpretations can be based. Examples of site datasets constructed for the Roman period of various parts of the Rhine-Meuse delta in the Netherlands are published by Willems (1986), Van Londen (2006), Vos *et al.* (2007), Vos (2009) and Kooistra *et al.* (2013). The database used in the 'Finding the limits of the limes' project is built on the foundations of an earlier dataset assembled by Ivo Vossen in his unpublished research, part of which was used in the study by Vos (2009). The project database was constructed by Philip Verhagen between 2013 and 2016 and first presented as a whole in the paper by Verhagen *et al.* (2016b), where besides a general introduction into the background and methodology, most emphasis was placed on dealing with the chronological uncertainties involved in such general site inventories. This chapter will present the archaeological site database used in this study and will for significant parts rely on that paper through summarising the information presented there, placing it in the context of this study, and expanding upon it wherever necessary.

3.2 Methodology

3.2.1 The site

The 'site' is a commonplace concept in archaeology, yet it often lacks a clear definition or delimitation in most smaller studies. In general, a place where archaeological artefacts, features, structures and organic remains are found together, or more simply a place where a substantial amount of anthropogenic traces are encountered, can be considered a site (Renfrew and Bahn 2004, 54). For studies on a regional scale, a standardised definition of the site concept is a necessity to be able to perform systematic analyses and interpretations with any degree of reliability. In that respect, a rather vague definition of 'a place with a substantial amount of anthropogenic traces' (cf. Renfrew and Bahn 2004, 54) is not a workable concept, as it raises questions such as what the lower limit is below which one can no longer speak of a 'substantial' amount of traces, or what the maximum extent of the 'place' is in which one can state that the found traces are in association with each other. Obviously, both are quite dependent on the nature of the archaeological site: an isolated farmstead will generally have a smaller archaeological 'footprint' than an urban settlement. The following paragraphs will detail the definition of what constitutes a site in the 'Finding the limits of the *limes*' project.

As stated above, a site is customarily constructed on the basis of anthropogenic traces. In most cases in the Dutch river area, this constitutes archaeological finds and features, the former of which may appear as surface finds but the latter of which are usually only discovered through archaeological excavations. Most archaeological information in the Netherlands is registered in the national archaeological database ARCHIS[1], where it is stored at the level of individual observations (essentially equivalent to findspots). An observation in the national database may be derived from any sort of research, ranging from the collection of stray finds by amateur archaeologists to large-scale archaeological excavations. Besides the ARCHIS data, which forms

[1] archis.cultureelerfgoed.nl

the majority of source data available to this study, information may also be retrieved from other surveys, examples being ones of phosphate concentrations (Steenbeek 1983), Late Iron Age coins (Roymans 2004), military gear in non-military contexts (Nicolay 2007) or *fibulae* (Heeren and Van der Feijst 2017).

To arrive at an archaeological site, an interpretation thus has to be made of the observation data. Willems (1986, 18) constructed a diagram that schematically describes this procedure (Fig. 3.1). One observation or multiple observations together form one site according to predefined criteria (section 3.2.2), which can be further interpreted to distinguish sites of specific types according to the activity that took place at that location (e.g. settlements or burials). However, observations can also be discarded during the first step (e.g. finds that have been moved through post-depositional processes such as fluvial activity) or can serve as the basis for a site of more than one type (e.g. a *castellum* and a *vicus*; see also section 3.2.3).

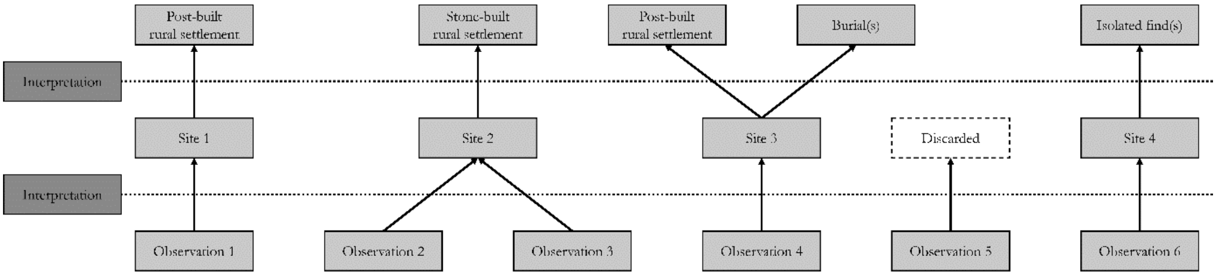


Figure 3.1. Possible processes encountered when constructing a site dataset from a set of observations. Adapted from Willems (1986, 18).

3.2.2 Rules for building a site dataset

The general procedures to construct an archaeological site database are thus quite clear and can be based on the methodology of preceding studies described in the previous section. The vital step that has to be undertaken is the systematic interpretation of observations to form the site dataset according to a set of predefined criteria. The first of these criteria is the number of finds in observations that are within a defined spatial range. Willems (1986, 90, with references) argues that this in reality varies from place to place depending on the nature of the evidence, as well as the intensity of research. A place that has been subjected to intensive field survey has a higher chance of a large number of finds than one that has only been passingly visited, and a handful of small sherd fragments does not have the same interpretative value as finds indicating household activities such as loom weights or querns. To define a place as a settlement, Willems (1986, 90), Vossen (unpublished, methodology briefly described in Vossen 2007, 40) and Vos (2009, 21) all use a minimum number of 10 finds. This criterion is adopted in this project to define an archaeological site in general (Verhagen *et al.* 2016b, 310), in order to systematically process the observation dataset in the most objective way possible.

The second criterion for defining a site is a certain spatial range in which observations are made. Bloemers (1978, 103) uses 250 m as the size of a rural settlement site, based on the size of the settlement of Rijswijk-De Bult which formed the central focus in his study of the Cananefatian *civitas*. Willems (1986, 89) states that most finds that together form a smaller settlement are usually found to be not more than 100 m, and only rarely further than 200-250 m apart, based on insights from excavations. He uses the latter values as a rule of thumb for the spatial delimitation of a site in his study on the Batavian *civitas*. This statement was repeated by Vos (2009, 21) in his study of the Kromme Rijn Region, who used the same dataset constructed by Vossen (2007, 40) that forms the foundation of the archaeological site database in this project. However, some larger settlements can be found to exceed the 250 m distance (Willems 1986, 89), which through this methodology could possibly result in a large settlement being split into two archaeological sites when it is not certain (e.g. through excavation) if two distant observations are associated or not. Based on a larger perspective on Roman settlement outside the Dutch river area, Nuninger *et al.* (2016, 5, with sources; see also Favory *et al.* 2012) set the extent of a Roman settlement territory at 500 m. Although this remains an arbitrary criterion, the limited extent of a settlement territory of 500 m, i.e. a radius of 250 m, is employed in this project to group observations into settlement sites (Verhagen *et al.* 2016b, 310). The centre of a site from which the 250 m radius is calculated is then either set as the observation with the highest number of finds, or set manually when the exact centre of the site is known for example through excavation (Verhagen *et al.* 2016b, 311), following the original methodology by Vossen (2007, 40).

3.2.3 Site interpretation

After defining an observation or a number of observations as an archaeological site, the next step is to assign an interpretation regarding the nature of that site. Willems (1986) generally makes a distinction between settlement sites, burial sites and isolated finds. He employs an array of evidence to define a site as a settlement: as a rule a settlement is established at a minimum of 10 sherds, but additionally the presence of a settlement soil or indicative finds such as spindle whorls or loom weights may also prove enough to call a site as a settlement (Willems 1986, 89). He makes a further distinction between the city (*Ulpia Noviomagus*), large settlements and small settlements, the latter of which can be post-built or stone-built, as well as military settlements (subdivided between the *castra* and other forts). Burial sites are subdivided by Willems (1986) into small (including isolated burials) and large ones (cemeteries). The isolated finds category then covers a range of sites including hoards, single coin finds, offerings and refuse sites (Willems 1986, 90).

Vos (2009) generally follows this earlier approach and for the Kromme Rijn region divides the settlement category between military settlements and civil settlements. For military settlements, he distinguishes *castella*, military *vici* and other (smaller) military settlements (e.g. watchtowers). Concerning the civil settlements, a distinction is made between small (1-3 houses) and large (>4 houses) rural settlements, and rural centres (>3-4 ha) (Vos 2009, 23–24). Besides direct evidence from excavations, larger settlements may also be distinguished through the size of an associated phosphate concentration. Stone-built rural settlements also appear in the Kromme Rijn region, identified through archaeological soil features (i.e. a 'robber trench', the trench that is left after removal of wall foundations) or through finds of large amounts of brick, tufa and roof tiles. They are assumed to always be part of large rural settlements or rural centres. However, due to the lack of data from excavations, many sites in the Kromme Rijn region had to be simply classified as 'undefined' rural settlements (Vos 2009, 45–47). Other site types that Vos (2009, 40, 54) distinguishes are burial sites and sites of road evidence.

In general, the site classification in this project follows the structure established in the preceding studies of the Dutch part of the Roman *limes*. The identified site types are presented in Table 3.1. Settlements are subdivided between military and non-military settlements (although the non-military settlements may still be associated with military ones, e.g. a *vicus* neighbouring a *castellum*). The military settlements can be further subdivided into the *castra*, military camps, *castella*, watchtowers, and undefined military settlements, whereas the category of non-military settlement distinguishes between larger civil settlements, stone-built rural settlements and regular rural settlements. Sections 3.2.3.1 and 3.2.3.2 present a more detailed definition of the used settlement categories.

Similarly to Willems (1986, 91), some in-site features that were encountered were added separately in the database to further specify the role that settlements can have, including *horrea*, glass kilns and pottery kilns. These features do not appear outside association with settlements. Following the precedents by the earlier studies, burial sites form a separate category. Cult sites were added as an additional category, as they are neither a settlement (but may be associated with one) or a burial site, yet form an important part of the social landscape. Many of the identifications as cult-site remain debatable, as they are sometimes only based on the presence of a large amount of coin finds (see also Aarts 2005). A fifth category has been added under the umbrella of infrastructure, indicating various constructions or places that are not settlements, and may or may not be associated with settlement sites. The final category that remains is that of isolated find(s), which sometimes have been specified as being shipwrecks or (hoard or offering) deposits, but also occasionally could not be distinguished further.

<table>
<tr><th colspan="2">Settlement site</th><th rowspan="2">Burial site</th><th rowspan="2">Cult site</th><th rowspan="2">Infrastructure</th><th rowspan="2">Isolated find(s)</th></tr>
<tr><th>Military settlement</th><th>Non-military settlement</th></tr>
<tr><td>• Castra
• Military camp
• Castellum
• Mini-castellum
• Watchtower
• Military settlement (indet.)</td><td>• Large civil settlement
• Stone-built rural settlement
• Rural settlement</td><td rowspan="3">• Burial site</td><td rowspan="3">• Cult site</td><td rowspan="3">• Aqueduct
• Bridge
• Canal
• Ford
• Harbour
• Jetty
• Road
• Waterworks</td><td rowspan="3">• Shipwreck(s)
• Deposit
• Isolated find(s)</td></tr>
<tr><th colspan="2">In-site features:</th></tr>
<tr><td colspan="2">• Horreum
• Glass kiln
• Pottery kiln</td></tr>
</table>

Table 3.1. Site types identified in the archaeological site database of the 'Finding the limits of the limes' project.

3.2.3.1 Military settlements

The subdivision in military settlements is mostly clear: *castra* are the large legionary camps, which in the Dutch river area concerns only those occupied in Nijmegen in the Early Roman Period A and the Middle Roman Period A. The first fortification was also the largest, measuring 42 ha, whereas the younger one measured only 16 ha. Also found only in Nijmegen, the category of military camps entails some smaller camps around the *civitas* capital that were temporarily inhabited between 10 and 20 AD.

The category of *castella* concerns the auxiliary forts that were mainly located along the Rhine, with a few additional ones in the hinterland. They are rectangular in shape and measure between 1.2 and 3.5 ha (Bechert and Willems 1995, 17). The mini-*castella* are a smaller variant that has been discovered in three places in the research area: two in the western Netherlands and one just across the border in Germany. This type is found more often along the German part of the Roman *limes* and is defined by Fleer (2004) as a generally square-shaped defensive structure larger than a watchtower, that encloses an area not greater than 0.3 ha. Watchtowers are the smallest intermediary military posts along the *limes* for surveillance and communication purposes (Willems 1986, 88; Bechert and Willems 1995, 18). This classification of military sites in essence does not differ from that of Willems (1986).

The final category is that of military settlements. They concern a number of settlements that have a military character based on finds and features that are specifically associated with the Roman military, but that are not further identifiable as belonging to a specific category.

3.2.3.2 Non-military settlements

The classification of non-military settlements has some differences compared to those of Willems (1986) and Vos (2009). Most importantly, no size-based distinction is made within rural settlements on the basis of the number of contemporary farmsteads, which is largely due to the lack of information available on a large number of settlements to support such a decision. Rural settlements that were classified by Vos (2009) as large rural settlements are therefore simply 'rural settlement' in this database. The distinction of stone-built settlements among rural settlements is maintained, but it must be kept in mind that most stone-built settlements likely only came into existence during the Middle Roman Period and often have a preceding post-built phase as well.

A major difference is also in the term 'large civil settlement'. Vos (2009, 23) employs 'civil settlement' as an umbrella term for all non-military settlements. In this project, the distinction is made between the smaller civil settlements (i.e. the post- and stone-built rural settlements described above) and the larger ones. In the research area, the sites interpreted as large civil settlements therefore include both the towns/cities of *Oppidum Batavorum*/*Ulpia Noviomagus* (Nijmegen) and *Forum Hadriani* (Voorburg) as well as the category that Vos (2009, 24) describes as 'rural centres', which follows the definition of Hiddink (1991, 224) as settlements that function as centres in rural contexts. The latter term also covers the interpretation of secondary centres used by Willems (1986, 267). Generally speaking, the rural centres are in between the *civitas* capitals and other rural settlements in terms of size, have some degree of craft specialisation but also still engage in rural activities, and in some occurrences play a role as a religious centre. The original intent for the introduction of 'rural centres' was to establish a definition to replace the term '*vici*', as it has not been consistently used over the course of the Roman period (e.g. referring to both independent settlements and neighbourhoods of cities) and thus does not always fit as the best description for what such settlements actually entail (Hiddink 1991, 201–2). Besides the cities, the term 'large civil settlements' therefore covers those settlements that have traditionally been described as *vici*, including both the rural and military ones (i.e. the *vici* commonly associated with Roman forts).

3.3 The site dataset

3.3.1 General

Following the methodology outlined in section 3.2, an archaeological site database was constructed for the Dutch part of the Roman *limes* on the basis of 9,465 observations. The total amount of sites present in the research area during any part of the Roman period is 1,322, and in total they have been assigned 1,583 site types (Table 3.2). In some instances this means that a site had multiple functions simultaneously (e.g. a settlement with road evidence), whereas in other cases a site had multiple functions separated in time (e.g. an Early Roman settlement and a Late Roman burial site). Of course this is still not equal to the total amount of sites that must have been present in the Roman period, since sites have inevitably disappeared through post-Roman erosion or have not yet been discovered. For the Kromme Rijn region, Vos (2009, 33) estimates that roughly 15% of the total set of archaeological sites remains unknown for these reasons.

Site type	Count
Castra	2
Military camp	1
Castellum	25
Mini-*castellum*	3
Watchtower	9
Military settlement	10
Large civil settlement	34
Stone-built rural settlement	39
Rural settlement	1085
Horreum	1
Glass kiln	1
Pottery kiln	2
Burial site	198
Cult site	26

Site type	Count
Aqueduct	7
Bridge	4
Canal	4
Ford	1
Harbour	7
Jetty	1
Road	108
Waterworks	6
Shipwreck(s)	3
Deposit	5
Isolated find(s)	1

Table 3.2. Number of sites divided by type (note: a single site may be categorised as more than one type).

Besides the site type, the database also contains the geographic coordinates, chronology, certainty of site identification and additional information related to each site. Furthermore, each archaeological site has links to the related observations on which the site is established and interpreted, which also contain references to the relevant literature. The inclusion of this source data is important to maintain transparency in the database and to allow for the dataset to be continuously used and updated in the future (Verhagen *et al.* 2016b, 311). In a different table, the observations are also linked to the individual archaeological finds that are contained within the observations, mostly derived from the national archaeological database ARCHIS. Section 3.4.2 presents how this find information can be employed to more dynamically approach the dating of sites.

3.3.2 Non-military settlements

As can be gathered from Table 2, a vast majority of sites in the region can be characterised as rural settlements. The spatial distribution of non-military settlements is presented in Figure 3.2. A total of 39 rural settlements were categorised as being stone-built, although there are some cases for which this interpretation remains speculative (see for example Vos 2009, 47–54 on the difficulty of proving the stone-built character of settlements in the Kromme Rijn region). In terms of spatial distribution, most stone-built settlements occur in the eastern half of the research area, which is not extraordinary since that is also were site density is generally greater and because it is in the vicinity of Nijmegen, the *civitas* capital. Most rural settlements are south of the Rhine, although some sites immediately north of the Rhine are included in the database as well. These inclusions may be useful for future research when discussing interactions across the Rhine, particularly regarding the Early Roman Period when the border was not yet solidified. Within the database, the set of stone-built settlements is entirely contained within the rural settlement set, meaning that a stone-built settlement is always also a rural settlement (and thus not all rural settlements in the database are post-built by default).

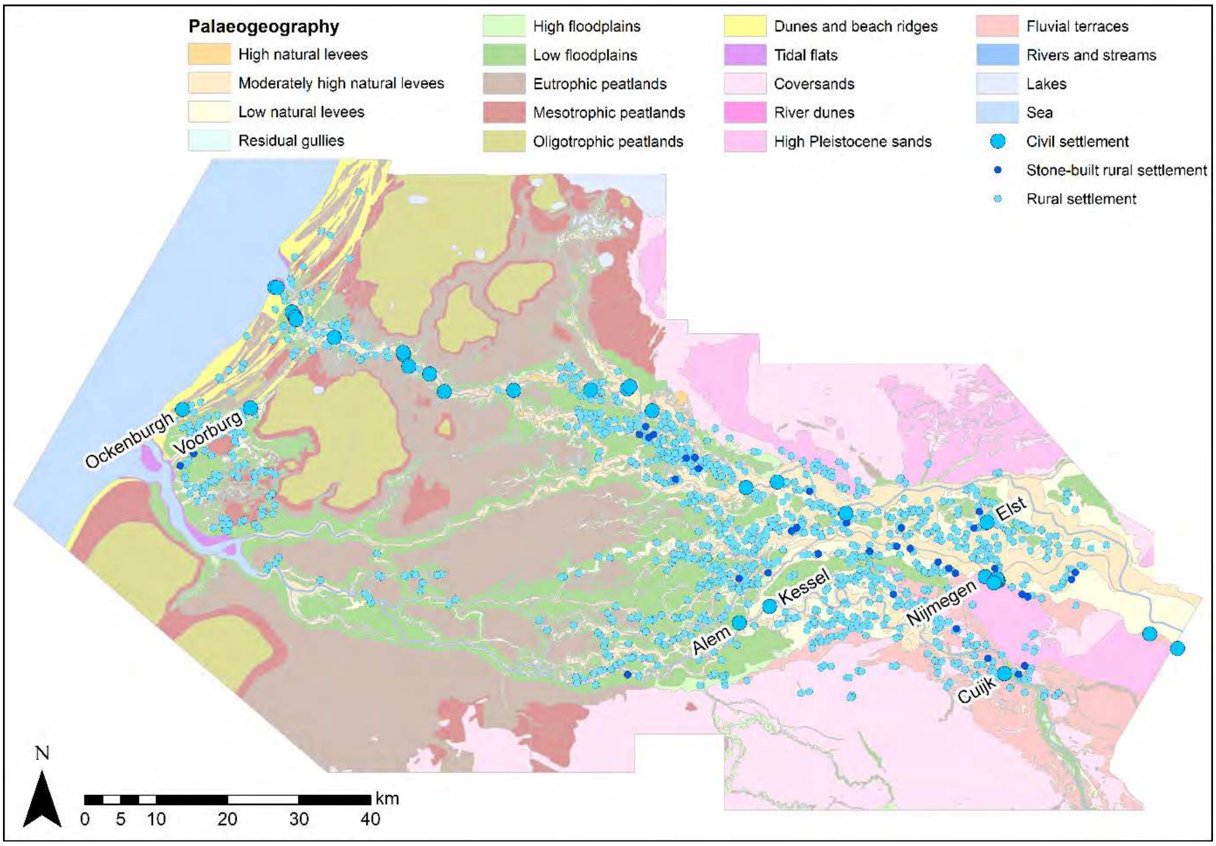


Figure 3.2. Diachronic overview of non-military settlements in the database, with place names for some large civil settlements that are mentioned in section 3.3.2.

A total of 34 sites were categorised as large civil settlements, which as mentioned in section 3.2.3.2 largely covers sites that were traditionally described as *vici*, both military and rural. In fact, most *vici* are found in close proximity to and in association with a (possible) military settlement, the exceptions being the rural centre at Elst and some sites that already functioned as rural centres prior to the establishment of a military presence such as Cuijk, Alem and Kessel (Roymans 2004, 103–48), or that remained after the abandonment of military structures such as Ockenburgh (Waasdorp 2012). This separation does not diminish the likelihood that the military-associated *vici* were morphologically and functionally similar to the non-military *vici* in the regional (socio-economic) structure (Willems 1986, 268; Hiddink 1991, 202). Other potential sites that have been proposed as rural centres/vici but were omitted as large civil settlements in the database include Wijchen-Tienakker (Heirbaut and Van Enckevort 2011; a *villa* site, registered in the database as a stone-built rural settlement) and Halder (Bink 2012; just outside the research area).

3.3.3 *Castra* and *castella*

An important focus of the 'Finding the limits of the *limes*' project is the relation between the rural population and the military population, and knowing the locations of the major military settlements is therefore of importance. This is unfortunately not always straightforward, as the location of some of the auxiliary forts (*castella*) along the Rhine is not certain, primarily due to post-Roman river erosion. Further clouding the discussion is the recurring focus of archaeologists and historians on connecting the place names registered in historical sources such as the Peutinger Table, the Antonine Itinerary and the Ravenna Cosmography to archaeologically known (and unknown) sites (e.g. Joosten 2003; Buijtendorp 2010, 714–21; Verhagen 2014), which can be an interesting and fruitful exercise in itself but is unfortunately riddled with inaccuracies and uncertainties due to the fickleness of the available historical and archaeological information. For this reason, this study aims to exclusively use the modern toponyms that are commonly associated with these military sites (mostly following Bechert and Willems 1995, 8) rather than their potential original names. An overview of the *castra*, *castella* and mini-*castella* sites that are included in the database is given in Table 3.3 and presented in Figure 3.3. What follows in sections 3.3.3.1-3.3.3.3 is a short description of these sites, with a focus on the (reliability of) spatial and chronological information, attempting to refer to original publications as well as recent syntheses/overviews of these sites wherever possible.

As Table 3.3. shows, the current interpretation is followed in which most of the Roman forts were abandoned at the end of the Middle Roman Period. Only a few were reoccupied in the Late Roman Period, possibly as part of a defence-in-depth system. However, there are indications for Late Roman activity at a number of forts, but the exact nature of this continued Roman presence is currently unknown (Van der Meulen 2017). Due to these uncertainties the Late Roman occupation phase of forts is currently mostly excluded in the database. This may be updated in the future, and any analyses in the current study based on this decision are of course repeatable.

Common name	**Type**	**ERP A**	**ERP B**	**MRP A**	**MRP B**	**LRP A**	**LRP B**
Along the Rhine:							
Katwijk-Brittenburg	*castellum*		■	■	■		
Valkenburg	*castellum*		■	■	■	■	■
Valkenburg-Marktveld	mini-*castellum*			■			
Leiden-Roomburg	*castellum*			■	■		
Alphen aan den Rijn	*castellum*		■	■	■		
Zwammerdam	*castellum*		■	■	■		
Bodegraven	*castellum*		■				
Woerden	*castellum*		■	■	■		
Vleuten-De Meern	*castellum*		■	■	■		
Utrecht	*castellum*		■	■	■		
Vechten	*castellum*	■	■	■	■		
Rijswijk	*castellum?*		■	■	■		
Maurik	*castellum?*			■	■		
Kesteren	*castellum?*		■	■	■		
Randwijk	*castellum?*			■	■		
Arnhem-Meinerswijk	*castellum*	■	■	■	■	■	■
Loowaard	*castellum?*	■	■	■			
Herwen-De Bijland	*castellum?*	■	■	■	■		
Along the Rhine in Germany:							
Rindern	*castellum*			■	■		
Qualburg	mini-*castellum*			■	■	■	■
Steincheshof	*castellum*			■	■		
Altkalkar	*castellum*		■	■	■	■	

In the hinterland:							
Ockenburgh	mini-*castellum*				■		
Rossum	*castellum?*	■	■	■	■	■	■
Kessel	*castellum?*						■
Cuijk	*castellum*					■	■
Nijmegen-Valkhof	*castellum*					■	■
Nijmegen-Hunerberg I	*castra*	■					
Nijmegen-Hunerberg II	*castra*			■			
Nijmegen-Kops Plateau	*castellum*	■	■				

Table 3.3. Sites identified as castra, castellum *or mini-*castellum *in the site database, sorted from west to east, with the time spans of occupation following the periodisation presented in Table 3.4. Note that in some cases a long occupation period may be the result of poor chronological information rather than a reflection of the reality.*

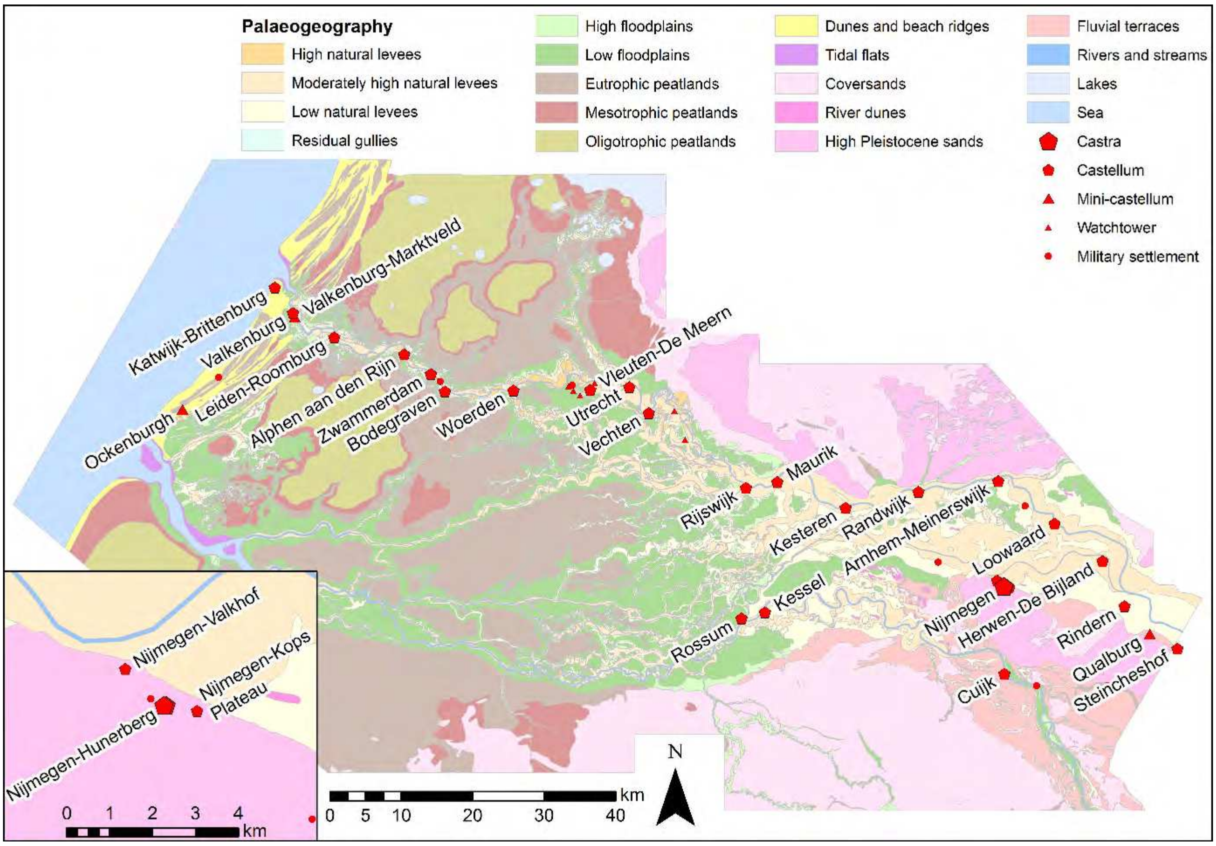


Figure 3.3. Diachronic overview of military settlements in the database, with place names for the castra, castella, *and mini-*castella *included in Table 3.3 and discussed in section 3.3.3. The inset shows a detail of the area around Nijmegen.*

3.3.3.1 Along the Rhine

The westernmost *castellum* of **Katwijk-Brittenburg** is one of the most mysterious forts along the Rhine, as it has disappeared under the seabed over the course of the 16th to 18th century. The oldest source detailing the archaeological site is an engraving by Abraham Ortelius from 1568. It has been tentatively dated between roughly AD 50 and 250, but this is only based on stray archaeological finds, of which it is not always certain whether they belong to the *castellum*, the nearby *vicus*, or to neither. A dating to the Late Roman period is sometimes suggested based on some characteristics of the towers in Ortelius' engraving, but this is likely erroneous and not corroborated by the finds (Bloemers and De Weerd 1984; Dhaeze 2011, 266–73). Its location is based on an analysis of the historical sources by Parlevliet (2002), although this is by no means conclusive and other locations have been proposed (e.g. Knul and Van Zoeren 2012).

The *castellum* of **Valkenburg** has largely been excavated and is one of the most thoroughly investigated forts along the Dutch part of the Roman limes. It was founded in AD 39 or 40. The fort was destroyed during the Batavian revolt of AD 69/70, rebuilt shortly afterwards and reconstructed in stone after AD 180. At its largest, the fort measured 150×170 m and has housed a half cavalry unit, and after the Batavian revolt a cohort of infantry. In the 4th century Roman presence was continued with at least three *horrea* constructed here. Just south of the *castellum*, another fortification was found at **Valkenburg-Marktveld**. This mini-*castellum* was occupied between AD 70 and 110, and was preceded by two *horrea* at this site along the *limes* road. It possibly housed units involved in the construction of the *limes* road in AD 99/100. A nearby watchtower was occupied only between AD 80 and 90 (De Hingh and Vos 2005).

The location and chronology of the *castellum* of **Leiden-Roomburg** are quite well-known based on excavation and prospection data. It was found to be constructed at least before AD 85, and presumably just after the Batavian revolt, although it may have been preceded by a smaller military settlement already from AD 47. Somewhere between AD 130 and 198 the fort was rebuilt in stone. The fort housed infantry and possible artillery units and could at least accommodate a 480-man cohort (Polak *et al.* 2004b; Brandenburgh and Hessing 2005).

A relatively large area of the *castellum* of **Alphen aan den Rijn** has been excavated quite recently, giving a good insight into the location and chronology of the site. It was constructed in AD 40-41, and burnt down during the Batavian revolt of AD 69/70. Some time after AD 160 it was reconstructed in stone. The fort had an approximate size of 80×120 m and accommodated infantry units (Polak *et al.* 2004a).

The *castellum* of **Zwammerdam** has been largely excavated in the late 1960s and early 1970s and is therefore quite well known. It was constructed around AD 47 and destroyed in the Batavian revolt. It was rebuilt after AD 80, and reconstructed in stone around AD 180. It measured 86×141 m and is thought to not be large enough to have accommodated a full cohort, but rather a smaller detachment which is assumed to have consisted of a mix of infantry and cavalry (Haalebos 1977; Franzen *et al.* 2000).

Bodegraven has been known to be a site with military presence for some time already, but the exact nature of the site has been a topic of discussion. Excavations only revealed a fort gate dating to AD 61, which burnt down during the Batavian revolt. Possible interpretations derived from this short-lived structure varied from a mini-*castellum* with an unusually large gatehouse, to an irregularly shaped or at least oddly oriented *castellum* (Van der Kooij *et al.* 2005, 298–99). However, a new inventory and analysis of the available data has proposed that it was likely a full-fledged and not atypical *castellum*, comparable in size to the neighbouring Woerden and Zwammerdam. It also revealed the possible presence of barracks and foundations for a stone-built phase, although actual stone remains are still missing. Archaeological finds indicate a continued occupation lasting into the first half of the 3rd century (Vos *et al.* 2016). The latter chronological information was not yet available at the time the data entry for the database closed, but it may be included in future studies.

The exact location of the *castellum* of **Woerden** was discovered in excavations of 1999-2000. The construction of the actual *castellum* is dated between AD 43 and AD 47, but it was preceded by a short-lived military settlement some tens of metres west of the younger site. It is postulated that the location shift is the result of movements of the Rhine channel or the nearby tributary stream (Van Dinter 2013, 22). The fort burnt down in the Batavian revolt and was rebuilt quickly afterwards. It was reconstructed in stone around AD 175, although some stone-built structures may have been present already in the 1st century AD. The fort measured approximately 90×140 m (Blom and Vos 2006; 2008).

The *castellum* of **Vleuten-De Meern** has been excavated intermittently until the 1980s (Kalee 1982; Isings and Kalee 1984) and subjected to archaeological prospection in the 1990s (Van der Gaauw and Van Londen 1992; Haarhuis and Graafstal 1993; De Jager 2000). Further intensive research has been carried out in the direct surroundings of the fort, revealing the course of the river and military road, the *vicus*, two watchtowers and a number of shipwrecks (Langeveld *et al.* 2010b). The fort was constructed around AD 40 and burnt down during the Batavian revolt. The fort was rebuilt firstly in wood and later reconstructed in stone. At one point (around AD 100) the fort was occupied by a naval unit, although there is no evidence if this was the case for the entire period of occupation. The youngest stone-built phase measured approximately 80×115 m.

A total of around 5% of the *castellum* of **Utrecht** has been excavated during several campaigns in the first half of the 20th century. The first construction of the fort is dated to approximately AD 50. During the Batavian revolt the fort burnt down, and it was rebuilt afterwards. It measured approximately 90×150 m, which is thought to have been large enough to house one 500-man infantry cohort. Around AD 210 the *castellum* was reconstructed in stone and became slightly larger, 123×151 m (Ozinga *et al.* 1989).

The site of **Vechten** has been excavated since the 19th century, and although documentation was initially poor, a number of reanalyses of the excavation data have been published in the last decades through which a reliable picture of the fort can be drawn (Polak and Wynia 1991; Kloosterman and Polak 2007; Zandstra and Polak 2012). It is the oldest and largest *castellum* in the Dutch river area, founded just before the start of the 1st century AD, contemporary to the fort of Haltern in Germany. It was destroyed during the Batavian revolt, rebuilt afterwards, and reconstructed in stone after AD 170. Occupation continued until at least AD 225, and probably until the third quarter of the 3rd century (Zandstra and Polak 2012, 247–60). A recent survey has yielded material evidence of occupation even until 300 and also in the late 4th and 5th century (Van den Berg *et al.* 2012, 87-88). After the Batavian revolt the fort measured approximately 2.6 ha and housed a full (double-sized) cohort and later a cavalry unit (Polak and Wynia 1991, 145–46). An old hypothesis that the fort initially served as a naval base is not strongly supported by the archaeological evidence, but cannot be entirely ruled out (Polak 2014).

Rijswijk is the westernmost *castellum* location that is not entirely certain due to fluvial erosion by the Rhine. It is only known from dredge finds with a distinctively Roman military character, discovered south of the modern Rhine near Rijswijk in 1978 and 1979 (Van Es and Blommesteijn 1979; 1980). Based on the finds, Van Es and Verwers (2010, 19–20) assume a life cycle similar to most other forts of the Dutch part of the Lower Rhine *limes*, meaning an occupation from halfway through the 1st century AD until the end of the Middle Roman Period.

Similar to Rijswijk, the location of a *castellum* near **Maurik** is also uncertain due to being known only from dredge finds near the modern Rhine, discovered in 1972 (Bogaers and Haalebos 1972). Based on tile stamps and *graffiti*, the fort was home to at least two different cavalry units between AD 70 and 116. Earlier occupation could not be proven (Haalebos 1976, 206–8).

Military presence in the vicinity of **Kesteren** is attested through the large number of finds of military nature in excavations of a settlement interpreted as a military *vicus* (Hulst *et al.* 1986), as well as in excavations of a burial site (Hulst and Bokma 1976). These finds support the earlier hypothesis of military presence near Kesteren (Bogaers 1974c). The supposed nearby *castellum* must then have been destroyed through fluvial erosion of the Rhine. However, an interpretation as a smaller military fortification can also not be excluded, since the assignment of the label *castellum* is also partly based on the association with the site of *Carvo*(*ne*) from the Peutinger Table and Antonine Itinerary (Willems 1986, 90; Verhagen 2014). The *vicus* was dated from AD 70 to 225, although some older finds are also present (Hulst *et al.* 1986, 29), on the basis of which Willems (1986, 239) assumes a slightly earlier foundation date for the *castellum* of AD 50. The exact location and dating of the site in the database thus remains relatively uncertain.

A possible *castellum* at **Randwijk** was hypothesised by Willems (1986, 251–52) not on the basis of finds, but rather on its position in the region with respect to the natural environment, other military structures, the limes road and other potential medium- to long-distance routes in the area. This hypothesis was tested by Heunks (2004), who concludes that a *castellum* in the vicinity of Randwijk is very plausible based on the aforementioned geographic arguments as well as some finds typical for such a military site, but that unfortunately its exact location cannot be determined due to post-Roman fluvial erosion. Both the geographic location as well as the dating of the site given in the database therefore remain tentative.

The *castellum* of **Arnhem-Meinerswijk** has been excavated in 1979 (Willems 1980; Willems 1986, 329–56) and 1991-1992 (Hulst 2001). Based on finds and features, the construction of the *castellum* is associated with the campaigns of Germanicus in AD 15-16 (Willems 1980, 338). It burnt down during the Batavian revolt, was rebuilt shortly afterwards and reconstructed in stone in the early 3rd century AD. The site was thought to be abandoned some time after AD 250 but at least before the end of the 3rd century (Willems 1986, 354). Based on extrapolations from the excavated main building, the dimensions of the youngest phase of the *castellum* are estimated to be between 102×170 m and 116×188 m (Hulst 2001, 427). Willems (1986, 354–55) also suggests a Late Roman reoccupation after a hiatus based on some finds of this period, but this remains uncertain. A Late Roman building phase is disputed by Verhagen and Wientjes (2008, 28).

The site of **Loowaard** is only known from dredge finds near the Pannerdensch Kanaal. Willems (1986, 256–57) interprets this site as a *castellum* based on find material of distinctly military character. Its location remains uncertain, as the finds are probably not *in situ*. The finds mostly date to the Middle Roman Period including large numbers of tufa and roof tiles indicating a stone-built phase. However, some finds are earlier, on the basis of which an Early Roman Period A start date is assumed (Willems 1986, 238).

Similar to Loowaard, the *castellum* of **Herwen-De Bijland** is only known from dredge finds discovered near the modern Rhine in 1938. Many finds of military character have been retrieved from this site, including a tombstone with epigraphic evidence for the site being named *Carvium* (Van Tol 1988, 295–97). The tombstone dates to AD 50, through which a small Early Roman military site is assumed, which was replaced by a *castellum* after AD 70. Based on the find material the site is thought to continue into the 3rd century and also to have a 5th century occupation phase (Bogaers 1974a).

3.3.3.2 Along the Rhine in Germany

A number of forts along the Rhine in neighbouring Germany are included in the archaeological database. This is done for two reasons: firstly, because the eastern extent of the Batavian *civitas* is not entirely known, but is thought to extend into modern Germany, making the inclusion of some forts in Germany a logical extension of the dataset. As a model the border is assumed to be halfway between Nijmegen and Xanten (*Colonia Ulpia Traiana* of the Cugerni), in the vicinity of the modern town of Kleve (section 1.3; Heeren 2009, 1). Secondly, many types of spatial analysis, such as path modelling (particularly concerning the *limes* road along the Rhine), would benefit from a starting point on (or even outside) the edge of the research area, to avoid so-called 'edge effects' (analysis results favouring the centre of a dataset due to a lack of data along the edges). The forts in modern Germany ultimately played a marginal role in the analyses performed in this study, mostly due to the lack of data on non-military sites across the German border. However, since the archaeological site dataset assembled in this project remains available for future research, the forts in modern Germany are left in for the aforementioned two reasons.

Finds related to the military site of **Rindern** were discovered during the demolition and reconstruction of the church of the town in the late 19th century. It was first occupied just after the Batavian revolt as a legionary winter camp, after which it continued as either a *castellum* or simply as a smaller intermediate station on the *limes* road until the end of the 3rd century (Follmann 1974; Willems 1986, 258).

The military site of **Qualburg** was probably founded after the Batavian revolt, although evidence is strongest for occupation in the 2nd century AD. It is interpreted as a mini-*castellum*. Based on the infills of the ditches the site is thought to have been abandoned around AD 275. It was reoccupied halfway through the 4th century, and finally deserted in the beginning of the 5th century AD (Bridger 1990).

The *castellum* of **Steincheshof** is a relatively young discovery. Initially thought to be a civil settlement or *villa*, surveys and geomagnetic prospection carried out between 2008 and 2010 revealed the presence of a fort (Brüggler *et al.* 2010). Small excavations have been carried out in 2010 and 2011 (Drechsler 2013). Early occupation of the site by a cavalry unit started already in the Early Roman Period A, but lasted only a few years. After the Batavian revolt the site was inhabited more permanently, likely by a full (double-sized) cohort. The fort of this period measured 125×180 m, and was finally abandoned between AD 171 and 200 (Drechsler 2013, 95–97).

The military site of **Altkalkar** was first occupied in the Early Roman Period A. The camp layout has been thoroughly mapped through geomagnetic prospection, although excavations have only taken place on a small scale. The first occupation of this site is evidenced by a moat, which was likely part of a smaller camp but cannot be dated. The first fort layout measured 190×170 m, and has been dated after AD 14. The finds indicate that the site has been continuously occupied until at least the end of the 4th century. At one point during this period the fort was scaled down to 140×170 m. As far as known it was occupied by cavalry units and was thus coined by German researchers as an *Alenkastell*, which in this case is not particularly larger than the *castella* of the Dutch river area (Wegner 1974; Bödecker *et al.* 2007; Berkel *et al.* 2015).

3.3.3.3 In the hinterland

The mini-*castellum* of **Ockenburgh** is one of the few military sites in the Dutch river area that is not located along the rivers. It is quite well known through excavations, and based on the find material it is most likely that it was occupied by a small part of a Roman cavalry unit (the stables could house only 16 horses at a time). However, this occupation lasted a relatively short period of time, namely from AD 150 to 180. The fort has possibly been part of a coastal defence-in-depth system along with other military settlements, including Den Haag-Scheveningseweg to the northeast. It must be noted that after the abandonment of the fort, the nearby large civil settlement continued to be occupied until roughly AD 250 (Waasdorp 2012; Waasdorp and Van Zoolingen 2015).

The sites of **Rossum** (with the nearby site of Alem) and **Kessel** (with nearby Lith) are traditionally associated with the places *Grinnes* and *Vada* respectively, which are known from the treatise on the Batavian revolt by Tacitus (*Hist.* V, 19–20). Both sites are recognised through a large number of finds retrieved through dredging. The complex of Rossum and Alem is interpreted as a large settlement that at one point was spread out across both sides of the Meuse. Military presence in Rossum is largely based on the association with *Grinnes*, as the presence of auxiliaries at this place is known through Tacitus. However, this interpretation is very uncertain and not strongly substantiated by the archaeological finds. Any military occupation around AD 70 was likely short-lived, and probably located on the south bank of the Meuse (near Alem) rather than the north bank near Rossum (Van Hemert 2010, 77). The material evidence of Kessel indicates the presence of a military fortification dating to the second half of the 4th century, possibly continuing into the early 5th century, as part of the Late Roman strategic reoccupation of the Dutch river area. This fort was located within the confines of the earlier *vicus* of Kessel/Lith on the south bank of the Meuse (Roymans 2004, 103–93).

Cuijk is primarily known as the site of *Ceuclum*, a place on the Peutinger Table on the road between Nijmegen and Tongeren and on a crossing of the Meuse. The presence of a *vicus* from the 1st to the 3rd century AD is well-established through excavations. A *castellum* was possibly occupied here for some time in the 1st century AD, although evidence is very limited (Haalebos *et al.* 2002b). A stronger case is made for a *castellum* from the early 4th century to early 5th century, which is paired with a Late Roman reoccupation of the settlement after a period of temporary abandonment (Haalebos *et al.* 2002a).

The area around Nijmegen has been home to a number of military sites. Roman military occupation in the Netherlands started with the construction of the *castra* at Nijmegen-Hunerberg, dated to 19 BC. It measured 42 ha and could accommodate two legions (Willems and Van Enckevort 2009). It was likely dismantled during or shortly after the departure of the legions on Drusus' campaign of 12 BC. Also around 12 BC, the site of Nijmegen-Kops Plateau was founded, which is suggested to have been a command post during campaigns of Drusus, Tiberius and Germanicus. Between AD 37 and 41 it was converted into a *castellum* housing one or more cavalry units, and continued to be occupied until the Batavian revolt (Van Enckevort and Zee 1996). After the Batavian revolt the site of Nijmegen-Hunerberg was reoccupied, the *castra* now measuring 16 ha. The legion left the site in AD 103 or 104, although a smaller force may have remained behind (Willems and Van Enckevort 2009). A final military occupation occurred in the Late Roman Period, when a *castellum* was constructed at Nijmegen-Valkhof (Van Enckevort and Thijssen 2014).

3.3.3.4 Sites rejected as possible **castella**

A number of other sites have at some point been considered as *castella*. They have not been interpreted as such in the database, instead being included for example as a smaller military settlement, a rural settlement, or not included at all. For some of the better known sites the interpretation will be discussed here. It should be worth repeating that the sites treated in the previous sections also have varying degrees of certainty regarding their interpretation. Fr example, Verhagen (2014) argues that the sites of Rijswijk, Kesteren and Loowaard (all known solely from finds retrieved through dredging) can be excluded as *castella* as part of his reinterpretation of the historical sources on the Dutch part of the Roman Lower Rhine *limes*. This only illustrates that while the current study makes use of the military sites included in the database outlined above, the list of sites rejected as possible fortifications may still expand in the future.

Willems (1986) discusses a number of sites along the Rhine in the eastern Rhine-Meuse delta that may have been Roman *castella* but that have not been treated yet in the previous section. Based on dredge finds the site of **Driel-Baarskamp** was interpreted as a cavalry fort, possibly a mini-

castellum, in combination with a wealthy settlement (Willems 1986, 252–55). Heunks (2003) has shown that the hypothesis for a *castellum* can be rejected, and interprets the site solely as a large rural settlement for which other (religious or military) functions cannot be excluded. It is therefore incorporated in the database as a rural settlement.

Further to the east, an excavation of the site of **Huissen-Hazeheuvel** in 1951 has yielded some evidence for a Roman fort (Bogaers 1974b). However, Willems (1986, 256) argues that these finds are out of context, and likely have been moved from another *castellum*, possibly Loowaard or Arnhem-Meinerswijk, in the Medieval Period. This interpretation is followed in the database.

Near the Meuse estuary, on the western stages of the southern main road through the Dutch Rhine-Meuse delta, the Peutinger Table lists a place by the name of *Flenio*. So far this toponym has not been univocally identified with an archaeological site. One of the options is Oostvoorne (Hessing 1995, 97), which falls outside the research area and will therefore not be discussed further. Another candidate is Naaldwijk, and a large excavation at the site **Naaldwijk-Hoogwerf** revealed evidence leading to a preliminary interpretation as a (civil or military) *vicus* near a *castellum* or fleet station (Van der Feijst *et al.* 2008, 208–9). However, further excavations and reinterpretation gave cause to change the *vicus* hypothesis, and the site has most recently been interpreted as a relatively large rural settlement with evidence for stone-built structures (Goossens 2012), and has been included in the database as such. It is still likely that there was a (naval) military site near the Meuse estuary at one point during the Roman period, but thus far its location remains unknown.

3.4 Chronology

3.4.1 Introduction

Although some sites (for example the excavated Roman military ones) can be dated quite precisely, the majority of sites in the database have only limited information available on which the chronology can be established. For this reason, rather than using exact time spans, the sites are dated according to the archaeological time periods used in the ARCHIS database (Table 3.4), which are based on the ABR.[2] It must be noted that these dates are crude and may be considered out-dated, for example regarding recent research on the transition from the Middle to Late Roman Period. However, such problems are outside the scope of this research, and this research therefore makes use of the established chronology.

The dates given in the database are most often based on archaeologists' expert judgement that is stated in the archaeological report(s) associated with the site, or on the dating assigned to the observations found in the ARCHIS database. Preferably, a site should be dated on the lowest level in the chronology, e.g. ERP A, ERP B, MRP A, etc. However, a site can also be dated relatively crudely to the Roman Period (the upper level in the chronology), which can either be interpreted as that it existed during the entirety of the Roman Period, or that it existed at one point during that time period but the quality of chronological information does not allow for pinpointing a more exact time span.

[2] *Archeologisch Basisregister* - Archaeological Reference Lists of the Netherlands.

Iron Age (IA)	Roman Period (RP)						Medieval Period
800 – 12 BC	12 BC – AD 450						AD 450 – 1500
Late Iron Age (LIA)	Early Roman Period (ERP)		Middle Roman Period (MRP)		Late Roman Period (LRP)		Early Medieval Period
	12 BC – AD 70		AD 70 – 270		AD 270 – 450		AD 450 – 1050
	Early Roman Period A	Early Roman Period B	Middle Roman Period A	Middle Roman Period B	Late Roman Period A	Late Roman Period B	Early Medieval Period A
250 – 12 BC	12 BC – AD 25	AD 25 – 70	AD 70 – 150	AD 150 – 270	AD 270 – 350	AD 350 – 450	AD 450 – 525

Table 3.4. Time periods as specified in ABR and ARCHIS, the Dutch national archaeological database. The Roman Period is subdivided between an Early, Middle and Late Period, which in turn are separated into two phases each. In contrast, the Iron Age is not distinguished on three levels.

3.4.2 Reinterpreting the chronological information[3]

With the original method of dating sites, described in the previous section, the dating quality and precision can vary greatly over the dataset, potentially affecting any further analyses. The variation in quality and precision is dependent for instance on the varying length of the archaeological periods, the number of observations per site, the number of reported finds per observation, but also on the quality of data entry in ARCHIS (Verhagen *et al.* 2016b, 311). When dealing with chronological uncertainties in the site dataset, two related questions can be posed: how can the quality of the chronological information be assessed; and how can the chronological uncertainty be employed to more suitably address archaeological problems?

One particular characteristic of the source datasets is the inclusion of individual find information in the observations used to construct the site dataset, which is a key component for dealing with chronological uncertainty in this methodology. More importantly, all of these individual finds have their own dating expressed in the archaeological periodisation (Table 3.4). A single find can thus also be dated to different levels of chronological detail, e.g. LIA-RP, which specifies a 700 year time span during which the find may have been deposited, or ERP A-MRP A, for a 162 year time span. These time spans can be converted into probabilities of existence of that find for each archaeological period ($P(t_i)$) by dividing the time span of that period (t_i in years) by the time span of the find (τ in years) (Eq. 3.1; Crema 2012, 446–47; Verhagen *et al.* 2016b, 311).

$$P(t_i) = \frac{t_i}{\tau} \qquad (3.1)$$

For example (see also Table 3.5), a find dated to LIA-RP has a P of 0.66 for the RP (450/700), a P of 0.12 for the ERP (82/700) and a P of 0.05 for the ERP A (37/700). Similarly, a find that is dated

[3] The content of this section is based on p. 309–313 of **Verhagen, P., I. Vossen, M. R. Groenhuijzen, and J. A. Joyce. 2016b. "Now You See Them, Now You Don't: Defining and Using a Flexible Chronology of Sites for Spatial Analysis of Roman Settlement in the Dutch River Area."** ***Journal of Archaeological Science: Reports*** **10: 309–21. doi: 10.1016/j.jasrep.2016.10.006.** Research design by PV, MG and JJ; data provided by PV, IV and MG; chronological reinterpretation by PV; case studies by PV and MG; discussion and conclusion by PV.

more precisely to ERP A-MRP A has a P of 1 for the RP (actually 450/162 = 2.78, but the probability of existence then equals 1), a P of 0.51 for the ERP (82/162) and a P of 0.23 for the ERP A (37/162).

	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
Find dating 1	LIA - RP						
$P(t_i)$	0.34	0.66					
$P(t_i)$	0.34	0.12		0.29		0.26	
$P(t_i)$	0.34	0.05	0.06	0.11	0.17	0.11	0.14
Find dating 2		ERP A - MRP A					
$P(t_i)$	0	1					
$P(t_i)$	0	0.51		0.49		0	
$P(t_i)$	0	0.23	0.28	0.49	0	0	0
Find dating 3				MRP A - LRP A			
$P(t_i)$	0	1					
$P(t_i)$	0	0		0.71		0.29	
$P(t_i)$	0	0	0	0.29	0.43	0.29	0

Aoristic sum	0.34	0.28	0.34	0.89	0.50	0.40	0.14
$p(0)$	0.66	0.73	0.68	0.32	0.47	0.63	0.86
$p(1)$	0.34	0.26	0.31	0.48	0.45	0.34	0.14
$p(2)$	0	0.01	0.02	0.18	0.07	0.03	0
$p(3)$	0	0	0	0.02	0	0	0

Table 3.5. Probability of existence of three hypothetical finds individually during each archaeological period, and based on this for each period on the most detailed level: the aoristic sum, and the probability of co-existence of zero, one, two and three find(s) (adapted from Verhagen et al. *2016b, Table 2).*

Addition of the probabilities of existence of all finds that are related to a site results in the aoristic sum of a given period (Ratcliffe 2000, 670–73; Crema 2012, 448). This can be seen as an estimate of the number of finds that are present at that site during that period, given an even distribution over the time periods according to their probabilities. The aoristic sum can be used to test the quality of dating per time period ($D(t_i)$), by dividing the aoristic sum ($\sum P(t_i)$) by the total number of finds registered to that period ($n(t_i)$) (Eq. 3.2; Verhagen *et al.* 2016b, 312).

$$D(t_i) = \frac{\sum P(t_i)}{n(t_i)} \tag{3.2}$$

For the hypothetical site of Table 3.5, the dating quality is given in Table 3.6. For the Roman Period, dating quality is highest for the MRP A, which is the result of the potential co-existence of all three finds, two of which are dated to relatively short time spans. Dating quality for the LRP B for example is much lower, since only one find is dated to this period, and it was dated to a relatively long time span. The high dating quality of the LIA is an anomaly in this, firstly, because this time period is always assigned a high probability based on its longer duration, which unlike the other time periods is not subdivided further on the most detailed level. The dating quality of a site is thus generally a measure of how precisely or crudely its finds are dated on average, and logically the difference between dating qualities becomes more reliable when a larger number of finds are associated with it. Verhagen *et al.* (2016b, 313) found that among sites interpreted as settlements, 29.2% had a good dating quality (average time span of finds <350 years), 44.2% had an average dating quality (350-700 years) and 26.6% had a poor dating quality (>700 years).

	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
Aoristic sum	0.34	0.28	0.34	0.89	0.5	0.4	0.14
Number of finds	1	2	2	3	2	2	1
Dating quality	0.34	0.14	0.17	0.30	0.25	0.2	0.14

Table 3.6. Dating quality per time period of the hypothetical site of Table 3.5.

While the aoristic sum can help to establish the dating quality of a site per time period, it is not a realistic proxy for site presence or absence during a period, as a find enters the archaeological record at only a single point in time, and not spread over several time periods. Establishing the probability of a site existing during a certain time period necessitates the calculation of the probability of co-existence (p) of an n number of finds during that period, shown in the bottom rows of Table 3.5 (Crema 2012, 449; Verhagen *et al.* 2016b, 311). For example, the probability of exactly two finds existing ($p(2)$) in Table 3.5 equals the sum of the probabilities of all configurations where two finds exist (P) and the other one does not ($1 - P$) (Eq. 3.3).

$$p(1) = \left(P_{find\ 1} \times P_{find\ 2} \times \left(1 - P_{find\ 3}\right)\right) + \left(P_{find\ 1} \times (1 - P_{find\ 2}) \times P_{find\ 3}\right) + \left(\left(1 - P_{find\ 1}\right) \times P_{find\ 2} \times P_{find\ 3}\right) \quad (3.3)$$

This is still relatively easy for a set of three finds, but it can be deduced that for larger datasets the calculation of probabilities quickly becomes more complex and computationally demanding. An alternative is to use a Monte Carlo-simulation approach of the number of finds per period (Crema *et al.* 2010), for which the average is then roughly equal to the aoristic sum. This was achieved through a Python script where a random number between 0 and 1 was compared with the probability of a find per time period, and if that random number was lower than the probability it was classified as being present in that period. A total of 1000 simulation runs were performed for each site, so that for example the occurrence of exactly 10 finds in a total of 100 runs is the equivalent of $p(10) = 100/1000 = 0.1$ (Verhagen *et al.* 2016b, 311–12).

As an example, the results for site 110 (Houten-Molenzoom) with a total of 70 associated finds are given in Table 3.7. The bottom rows show that there is quite a good correspondence between the average number of finds per period derived through Monte Carlo-simulation and the calculated aoristic sum. More precisely, a comparison through a paired T-test of the aoristic sums and the simulation results (H_0: $\overline{\sum P(t_i)_{aoristic\ sum}} = \overline{\sum P(t_i)_{simulation}}$) gives P-values approaching 1 for the majority of sites, indicating that the difference between the two is not significant. Only one site (site 1019) had simulation results that were significantly different from the aoristic sum (P-value of 0.029), which is probably a result of it having only two finds associated with it in the database (it was interpreted as a site based on the presence of a settlement soil), and it appears to be a random occurrence since other sites with so few finds do not pose the same problem.

Number of finds	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
0	0	15	1	0	0	1	0
1	0	65	5	0	0	8	0
2	9	135	26	0	0	35	9
3	32	196	49	0	0	81	15
4	115	206	92	0	0	134	53
5	203	159	145	0	0	152	100
6	248	102	163	1	1	144	104
7	184	68	181	2	0	162	169
8	119	26	151	5	2	126	158
9	60	16	81	8	7	75	137
10	19	10	52	18	20	38	116
11	8	2	35	27	33	24	67
12	3	0	13	48	56	10	37
13	0	0	3	89	76	3	19
14	0	0	3	104	99	4	9
15	0	0	0	103	121	3	3
16	0	0	0	135	144	0	3
17	0	0	0	112	117	0	1
18	0	0	0	96	110	0	0
19	0	0	0	92	76	0	0
20	0	0	0	69	47	0	0
21	0	0	0	34	35	0	0
22	0	0	0	23	27	0	0
23	0	0	0	17	17	0	0
24	0	0	0	8	9	0	0
25	0	0	0	7	0	0	0
26	0	0	0	2	2	0	0
27	0	0	0	0	0	0	0
28	0	0	0	0	1	0	0
29	0	0	0	0	0	0	0
...	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0
Average	6.17	4.10	6.62	16.29	16.18	6.20	7.90
Aoristic sum	6.09	4.24	6.95	16.01	16.26	6.15	7.69

Table 3.7. Results of 1000 simulations of site 110, for each period giving the number of runs in which that exact number of finds occurs.

Based on the principle that a site is assumed to have existed when at least 10 finds were present on that location (which was used as a rule for the original creation of the dataset described in section 3.2.2), the probability that site 110 existed in the LIA is equal to the number of runs (r) with 10 or more finds divided by 1000 (Eq. 3.4).

$$p(\geq 10) = \frac{\sum_{n\geq 10} r}{1000} = \frac{19+8+3}{1000} = 0.03 = 3\% \tag{3.4}$$

Similarly, the probability for the site being present in the MRP A is 0.984 (98.4%) (Table 3.8; Verhagen *et al.* 2016b, 312). These values can be used in further (spatial) analyses, as a site dataset can be constructed that is based on probabilities of presence during a certain time period, rather than the original chronological information of varying quality and precision. This solves problems such as including sites that are dated relatively crudely to the RP in an analysis on a more specific time period such as the MRP A, since all sites now have probabilities defined on the most detailed levels. When using a minimum probability threshold of 50% for any period, the size of the dataset of sites interpreted as settlements decreases to 58.4% of the original, indicating that 41.6% of the sites cannot be reliably included in any time period using this arbitrary threshold. The majority of unreliable sites seems to be lost already at the 50% threshold, since raising the minimum probability threshold to 80% or 99% only decreases the dataset size further to respectively 54.6% and 44.3% of the original (Verhagen *et al.* 2016b, 312).

Number of finds	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
<10	0.970	0.988	0.894	0.016	0.010	0.918	0.745
≥10	0.030	0.012	0.106	0.984	0.990	0.082	0.255

Table 3.8. Probabilities for site 110 for the presence during each period of less than ten finds, and the presence of ten or more finds, based on 1000 simulations.

3.5 Conclusion

The aim of this chapter was to present the archaeological site database that is used in this project, with all the intricacies involved in its construction that may be relevant in later analysis. This includes the used definition to translate a set of observations (find spots) to a site (section 3.2.2), the interpretation of site types (section 3.2.3), as well as the establishment of site chronologies (section 3.4).

Especially the aspect of reinterpreting the chronological information associated with sites was treated extensively, particularly in the paper by Verhagen *et al.* (2016b), from which the methodology was repeated here in section 3.4.2. Applications of this approach that have been carried out in the context of this project include studies on the development of settlement density throughout the Roman period (Verhagen *et al.* 2016b, 313–14), site location analysis (Verhagen et *al.* 2016b, 314–16; Chapter 7) and the study of transport networks (Groenhuijzen and Verhagen 2017; Chapter 6).

4 Characterising transport systems in the Dutch part of the Roman *limes*

4.1 Introduction

One of the clearest ways in which the territory of the Roman Empire was structured was through the construction of an infrastructural network. In our research area this is represented by two military roads that are quite known from historical sources, one connecting the *castella* along the Rhine and one running a more southern course along the Waal and Meuse (Fig. 4.1). In addition, a number of 'secondary' roads must have been present, as has been attested in archaeological finds (Van der Heijden 2011, 32), as well as numerous 'routes' linking even the smallest settlements to each other and to the regional network. Furthermore, water-based transport is not to be overlooked, as shipping must have been an important part of the infrastructural network in the Dutch river area. Particularly in the 1st century AD most, if not all, supraregional transport of bulk goods must have occurred over water, considering that construction of the earliest attested *limes* road in the Netherlands did not begin until almost a century after the establishment of the first *castella* (Graafstal and Vos 2016, 47–49; although there could have been a precursor that is not known from archaeology, possibly along the river Vecht towards the fort/naval base at Velsen). The total of all these connections created a fine and intricate network of which we have only scratched the surface in regular archaeological research.

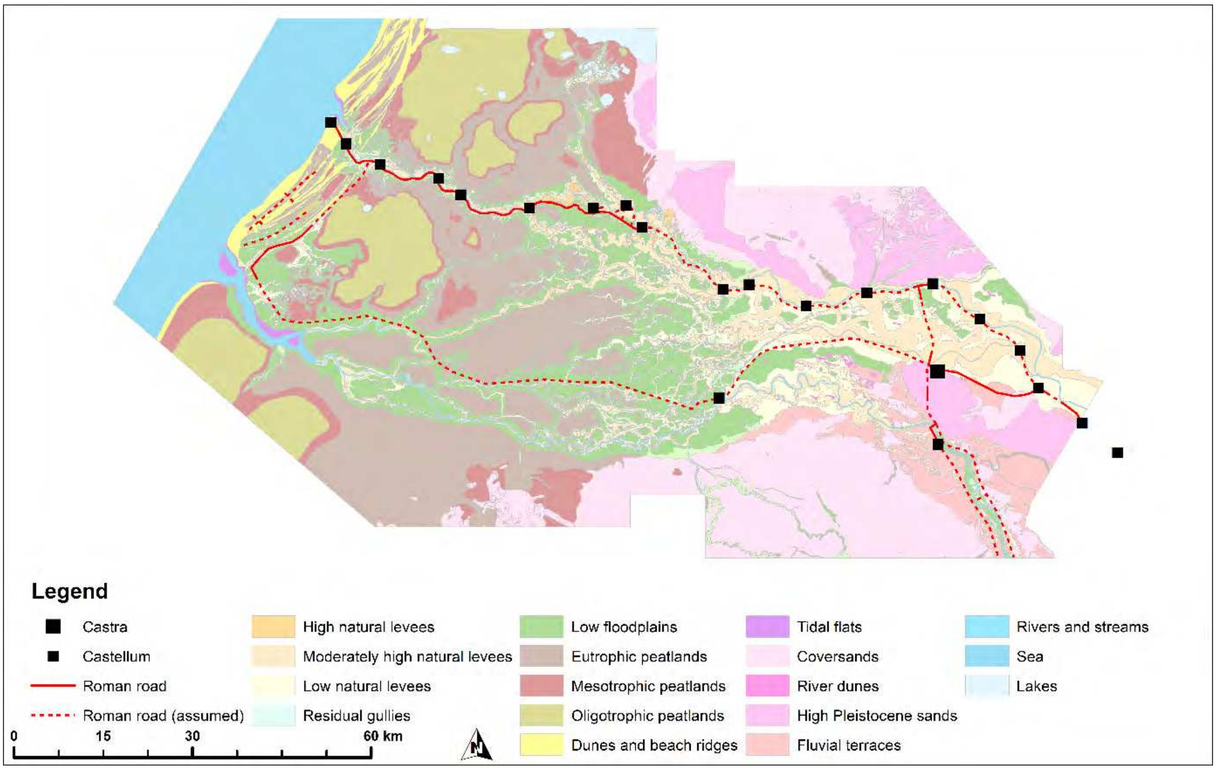


Figure 4.1. Main roads in the Dutch part of the Roman limes*, following Van Dinter (2013), Graafstal and Vos (2016, 46) and Van Dijk and Dolmans (2016, 81).*

One of the aims of this study is to reconstruct and analyse transport networks that were active in the region, by identifying and quantifying the factors that govern movement in general as well as the movement of goods in particular. Analysis of transport networks of the past that are reconstructed using this information can not only tell us something about the functioning of transport networks themselves, but also about the actors that were working in those networks in the past. The entire discussion on Roman transport networks in the Dutch *limes* zone is split over three chapters. The current chapter will deal with the characterisation of transport, particularly for the Dutch part of the Roman *limes*, but when necessary sources for other time periods and areas will be included as well. The following Chapter 5 deals with the modelling of transport connections, and after that Chapter 6 concerns the construction of networks and the studying of those networks through the application of analytical methods of network science.

4.2 Transport characterisation

Transport is the subset of movement or mobility where people, animals, goods or information are transported from one location to the other. By definition, transport cannot exist without moving people, goods or information around as the outcome of demand or supply (Rodrigue *et al.* 2006, 2). In other words, transport is the part of movement when someone or something is moving or being moved for a purpose. This section will explore the various ways in which transport takes form through a number of characterising parameters, starting with the scales of transport and transport agents. It will be followed by addressing the purpose of transport and the frequency and timing of transport. The modes of transport available in the Dutch part of the Roman *limes* are an especially important characteristic of transport, particularly for the modelling of transport connections, and are therefore treated separately in section 4.3.

4.2.1 Scales of transport and transport agents

Due to the arrival of the Roman military community at the start of the Roman Period, the number of transport movements must have greatly increased as a result of the social and economic interactions between the military and the local population. An important next question would be: who is transporting? In the following section 4.2.2 various goals of transport will be outlined, but since our interest lies mainly in the movement of goods for sustenance of the rural, military and urban populations, the focus will be on the agents of economic transport. Firstly, an important distinction has to be made based on the aspect of the scale of transport movements. Goods can be moved over relatively short distances from rural settlements to local markets, or over large distances, such as the transport of grain over provincial borders (Willems 1980, 342; Pals and Hakbijl 1992; Kooistra 2009). In her study of pottery exchange networks in the Tungrian *civitas*, Van Kerckhove (2015; Table 4.1) distinguishes three interconnected networks: an imperial exchange network, interprovincial exchange networks and regionally centred, provincial exchange networks. The latter can be further subdivided into interregional networks (between *civitates*), regional networks (within the *civitas*) and local networks (between settlements).

<table>
<tr><td colspan="2">Imperial (empire-wide trade)</td></tr>
<tr><td colspan="2">Interprovincial (empire-wide trade)</td></tr>
<tr><td rowspan="3">Provincial (within provincial border)</td><td>Interregional (between civitates)</td></tr>
<tr><td>Regional (within the civitas)</td></tr>
<tr><td>Local (between settlements)</td></tr>
</table>

Table 4.1. Interconnected networks on different scales, according to Van Kerckhove (2015, 250–251) in her study on pottery exchange networks.

The bulk of the transport that exceeds the extent of the research area, i.e. transport on imperial and interprovincial scales, will likely consist of the import of goods that the region is lacking, and a potential export of goods that the region has a surplus of. A shortage of goods can often be instigated by the presence of a Roman military camp, as there is mostly no relation between an army's requirements and local production capacity, the army's presence instead being the result of political and military choices (Finley 1985, 91). This is the case for the Dutch part of the Roman *limes*, where the Roman military placed a heavy burden on local production, to the point where import was necessary to fulfil the army's demands (Van Dinter *et al.* 2014). This kind of supraregional transport was likely handled by specialised agents either independent or directly employed by the government or the military. So-called *negotiatores frumentarii* (grain traders) were specialised in collecting goods from distant regions, often working far away from the army unit they are serving (Carreras Monfort 2002, 77). In addition, individual private traders may have supplied the army with goods that are consumed in smaller quantities from supraregional sources (Carreras Monfort 2002, 85). According to Paterson (1998, 160), the *negotiatores* constitute the wholesalers that finance trade and transport on large scales, while the *mercatores* are responsible for the transport itself and the sale of transported goods, although *negotiatores* may also act as *mercatores*. *Navicularii* and *nautae* are their respective equivalents in the shipping industry, and their roles may also overlap. Evidence for these professions also being active in the Dutch Rhine-Meuse delta was found on votive stones (Fig. 4.4; Bogaers-Stuart 2001, 34–37; Habermehl 2011, 140).

Figure 4.4. Two votive stones from the Dutch river area mentioning a negotiator frumentarius *(left) and* nautae *(right) (from Habermehl 2011, 140; originally from Willems 1990, 68 and Hessing* et al. *1997, 66).*

The primary interest of this study is on transport within the research area, and particularly concerning transport between the local and the military population. The first level here pertains interregional transport, meaning the movement of goods or people over larger distances (across *civitas* borders), but still within the region contained by the research area, namely the Batavian and Cananefatian *civitates*. The second level concerns regional transport, i.e. transport within a *civitas*. The width of the research area is approximately 150 km, meaning that it cannot be travelled within a day, perhaps with the singular exception of a horse relay system along the military roads (Scheidel *et al.* 2012, 20). In general, Roman armies aimed to supply their troops directly from the local territory, meaning its direct vicinity. However, a less densely populated border region with a large military presence such as the Dutch *limes* was not able to support the *castella* locally, likely resulting in the entire hinterland of the *limes* participating in the provisioning of the Roman army in addition to resources being imported from outside the province (Van Dinter *et al.* 2014; De Kleijn 2018, 125-201; Joyce in prep.). Responsible for the financial matters of a province were the *procuratores augusti*, controlling all direct and indirect taxes as well as the government purchases of goods on the market (Remesal-Rodríguez 1990, 59). Usually the *procurator* assigned a sum of money to army units to obtain supplies from local markets, but when the Roman armies could not locally obtain their required resources, it was the *procurator*'s task to acquire the necessary goods from provincial *mercatores* or foreign traders, and redistribute them through public or private transport networks, sometimes employing military to undertake the transport (Carreras Monfort 2002, 75). It is thought that contact of the local population with the military initially went through the economic relations with the markets and urban centres (Bloemers 1990, 115).

The lowest scale level of transport concerns the transport over relatively short distances, i.e. local scale transport. An example is the transport of goods from settlements to local markets, the majority of which likely concerned agricultural surplus production. There was possibly some amount of transport between settlements, for example when one or more settlements experienced a bad harvest and were supplemented by nearby settlements, although there is no archaeological or literary evidence to support this. Regarding other material goods, there was probably very little 'horizontal' exchange between local settlements. Goods such as pottery were largely distributed through a vertical system with local markets and centres functioning as mediators (Willems 1986, 421; Vos 2009, 228). For Roman Italy it is argued that transport on this level of scale is largely self-sufficient, using the animals and workforce already available at the farm to move goods to the local markets (Laurence 1998, 136). Considering the mostly self-sufficient nature of society in the Dutch river area prior to the arrival of the Romans there is little reason to believe it would be different among the Batavians and Cananefatians.

4.2.2 Purpose of transport

The purpose of transport can vary. Ones that can immediately be thought of are transport through economic market forces, social interaction, political representation or military action. Economic transport, which generally concerns the transport of commodities between production, market and consumption sites, may be the most frequently studied and most quantifiable aspect of transport, as will be shown also in later sections. Quantified transport studies look at quantitative aspects such as capacity, speed or cost of transport. The research done in this field in archaeology mostly covers transport on regional to supraregional scales (e.g. Duncan-Jones 1974; Laurence 1998; Arnaud 2007; Carreras-Monfort and De Soto 2013; Scheidel 2013; 2014), and is not concerned with transport on the local scales, with the exception of path reconstruction studies based on least-cost principles (e.g. White and Surface-Evans 2012; Polla and Verhagen 2014).

A large part of transport movements occurring in the research area must have been at least partly of an economic nature. In the preceding Late Iron Age, the rural population in the Dutch river area formed a subsistence economy, or as Hopkins (2013, 102) describes, an 'economically unsophisticated region'. Although not immediately (e.g. Groot *et al.* 2009), a change occurred in the economic structure of the region with the arrival of the Romans and the establishment of the Roman frontier in the research area. Local production for local consumption was likely preferred, as was the case throughout the Roman Empire (Harris 2007, 716). However, the Roman army could (and likely needed to) rely at least in part on imports from outside the region. However, moving bulk goods across large distances was a costly procedure and a significant part was only made possible through state facilitation, a prime example being the grain supply to Rome from across the Mediterranean (Finley 1985, 126; Harris 2000, 717; Mattingly 2007, 224).

As stated above, the Roman occupation of the Dutch river area placed new demands on the local rural population, such as taxation, which could have been in the form of surplus production (or manpower for the Roman army in the Early Roman Period) or in the form of money that was raised by selling produce at local markets. The introduction of surplus production and taxation in former subsistence economies also allowed the start of division of labour and the rise of artisans producing goods other than staple foods, leading to possibly a number of people working solely for the needs of the Roman military on the frontier (Hopkins 2013, 101–3). The newly arising economy with unprecedented supply and demand structures must have greatly increased the number and scale of transport movements, particularly those of staple foods from production sites to markets and consumption sites. How people are integrated into the economy can be defined in several ways, although the difference is mostly terminological rather than conceptual (Temin 2001, 170–71). Pryor (1977) offers a useful definition, by distinguishing between exchange and transfers. Exchange can be subdivided into market exchange, where the ratio of goods or services exchanged can vary and which can include exchange for money, and reciprocal exchange, where the ratio does not vary (e.g. gift-giving practices). Secondly, he distinguishes transfers, when there is no immediate return for the transaction of goods or services. They can be subdivided into centric (e.g. taxation) and non-centric transfers (e.g. theft). Taxation of the rural population for the provisioning of the Roman army is thus an example of a centric transfer.

While all manners of transport are in essence social as transport is a way of connecting people and places to each other, defining a separate category for social transport is perhaps necessary for a part of purposeful yet not clearly economic transport. A goal of such social transport can be the communal gatherings at sites of regional importance, for example. Most notably in the Batavian area are three major cult sites, namely Elst (Fig. 4.2), Kessel and Empel, all devoted to Hercules Magusanus (Fig. 4.3), who supposedly played a major role in the Batavian origin myths. The temples are attested to have pre-Roman origins and have kept their central role in the Batavian *civitas* until their destruction in the first half of the 3rd century AD (Roymans 2004, 12). They are assumed to have functioned as large gathering places where the ethnic identity of the community and the boundaries with external groups were cultivated (Roymans 2004, 246). From the Cananefatian *civitas* little is known about similar cult practices of regional importance, although some smaller rural cult places have been identified (Van Zoolingen 2011). Just south of the Cananefatian *civitas* two major cult places dedicated to Nehalennia are identified near Domburg (Hondius-Crone 1955) and Colijnsplaat (Stuart and Bogaers 2001). The goddess of Nehalennia is known to have played an important role in overseas trade (Stuart 2003).

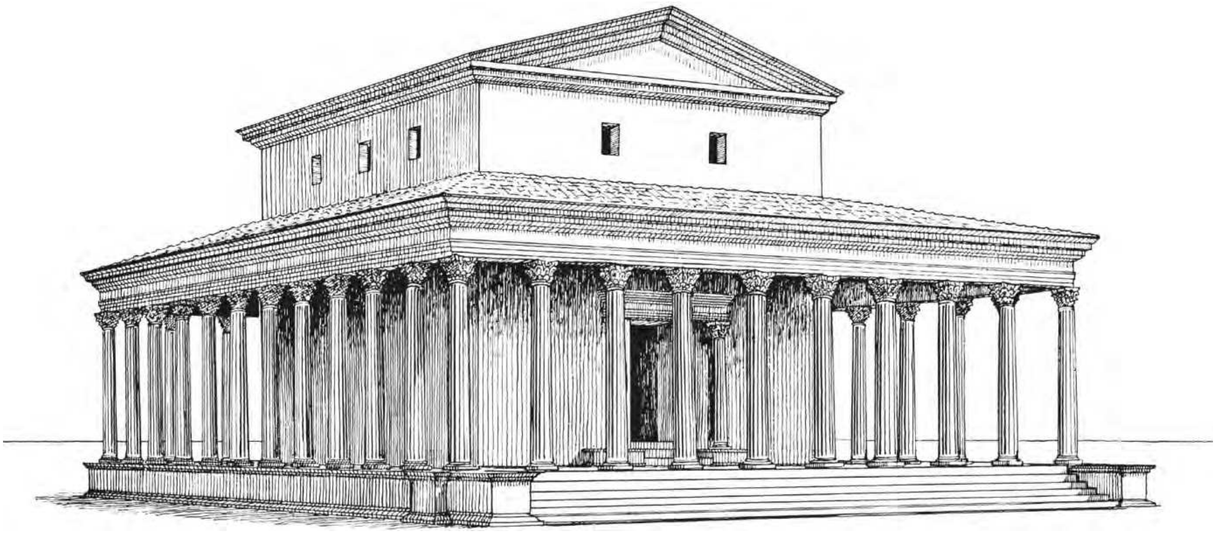


Figure 4.2. The 2nd-3rd century phase of the Gallo-Roman temple of Elst-Sint Maartensstraat (from Derks et al. *2008; originally from Bogaers 1955), one of two temples found in Elst.*

Cult places of regional or even interregional importance must have functioned as important centres in social networks. Although not necessarily used frequently, routes leading to the cult places must have been well known among the rural population. The importance of such places in social networks and possibly infrastructural networks has also been recognised by researchers of the Roman Netherlands such as Willems (1986, 68), who placed Elst at the cross-road of a north-south route connecting the settlements and forts of Cuijk and Nijmegen to a supposed fortification on the Rhine near Driel, and an east-west route connecting the forts of Herwen-De Bijland and Loowaard to both the fort of Randwijk on the Rhine as well as the northern bank of the Waal west of Elst. While the location of a *castellum* near Driel is very uncertain with only some isolated finds in the area, the north-south connection over the natural levee by way of Elst is also the most logical route to the fort of Arnhem-Meinerswijk, which means this possible connection cannot be disregarded.

Figure 4.3. Bronze figurine of Hercules Magusanus (from Roymans and Derks 1994).

Other movement of people may be as part of the political landscape, such as wealthy and/or influential individuals from the rural hinterland travelling to the *civitas* capital in their function as *decuriones* (Willems 1986, 427; Vos 2009, 228; Derks 2011; Hopkins 2013, 121). The entire political system, where the central Roman government was not directly involved with its subjects but rather through intermediaries, must have necessitated a more intense network of interactions in comparison to the preceding Late Iron Age. This political network then probably revolved around one or a few central nodes, including the *civitas* capital and possibly a number of local centres.

Military transport is another form of transport of extraordinary nature, in that it is not entirely governed by the markets of supply and demand, but also by strategical decisions. The supply of food and other resources across large distances over well-organised supply lines is one of the key factors that made the Roman army successful during their campaigns (Roth 1999, 279). The transport of the army itself and the goods it is carrying is even almost entirely non-economic: the goal of moving is mostly fuelled by political or strategical choices and demands. Labisch (1975) has developed a model for the supply lines for the movement of goods during Caesar's Gallic wars that distinguishes between strategic, operational and tactical bases. The strategic base is defined as the source of provisions outside the area where the army is operating, which can even denote entire provinces that are supplying an army in the field elsewhere (Roth 1999, 223). The operational base is where the army gathers supplies within the area it is operating, which is usually the gateway where the bulk of the goods arrive, such as a port. Moving along with the army is the tactical base, a camp in close proximity to or even within the army's camp. Between the latter two a continuous supply line was maintained (Roth 1999, 157). However, the period of Roman armies campaigning through the research area was already over during the timeframe of this study, with the Roman *castella* well established and the frontier solidified during the Early Roman Period. Military transport will thus not be further considered, as the supply of the military population in the Roman fortresses can be captured in regular (socio-)economic models.

A complicating factor in the matter of transport is that there are intangible factors that influence the shaping of it, of which we may only have limited knowledge from historical sources. One example is the allocation of a strip of land along the *limes* primarily for the grazing of animals belonging the military, with this strip of land being kept free of settlements (Tacitus, *Ann.* XIII, 54–55; Bloemers 1978, 97–99; Willems 1986, 415; Vos 2009, 32). While it does not directly indicate any hindrance for transport across the reserved areas, a lack of settlements that function as start or end points of transport will likely decrease the frequency of movement along these corridors. This could have been negated by the presence of a superior infrastructure in the form of the Roman *limes* road and the presence of the Roman *castella* and *vici* themselves, although it remains the question to what extent the local population made use of military infrastructure, or maybe was even allowed to use it. Furthermore, the presence of constructed roads is not a game-changing benefit for rural transport, as the main limitation is not in infrastructure but in the mode of transport that is used (Finley 1985, 126–27; see also Chapter 5).

4.2.3 Frequency and timing of transport

There is very little archaeological or historical information on the frequency or timing of transport movements, and the little that is available relates to long-distance transport. Examples are sources on the viability of shipping on the Mediterranean Sea and the Atlantic Ocean (see Scheidel 2014 with references) and road transport in the Alps (e.g. Hunt 1998) during the winter seasons. In one case, in a study of the *villa* of Settefinestre on the Via Aurelia, it was shown that transport was carried out over sea during the summer and over land during the winter (Laurence 1998, 143). Unfortunately, regarding local (economic) transport we can mostly only make some inferences based on the relation of transport with other activities. Some activities are undertaken almost throughout the year, for example pertaining arable farming, animal husbandry and wood collection. Transport related to the practice of these activities must then also have occurred throughout the year. However, the bulk transport of goods, either for the market, as tribute or taxation, can only have occurred during specific times of the year, namely outside the harvesting season. The reason for this lies in the availability of the workforce. Since labour is the main limiting factor of agricultural production in the harvesting season (Joyce in prep.), the majority of the available workforce would have been unavailable for transport. Furthermore, travel over land as well as on rivers may have been limited during the colder seasons due to weather and terrain conditions. Buisman (1995, 378–79) discusses the effect of the seasons on travelling in the Medieval Period, and outlines that summer was the best time for travel due primarily to the higher temperatures and longer days, although the hot midday temperatures and mosquitos may prove a nuisance for travelling as well. Travel was possible during spring and autumn, but made more difficult by the muddy roads and paths, cold winds and unpredictable weather shifts. Winter was generally avoided due to the coldness, wetness and the possibility to get stranded on muddy and snowy roads and paths or before an overflowed river. Shipping also ceased in the winter period due to the unpredictability of rivers. However, the rivers could freeze over during very cold winters, creating alternative and fairly accessible corridors for travel, although the danger of snow, rain or rapid thaw remained (Buisman 1995, 378–79). Although the Roman Period is characterised by a slightly warmer climate than the Medieval Period (McCormick *et al.* 2012), the general difficulties for transport in the colder seasons will have been quite similar.

These recurrent limitations on transport do not have to be a problem for the movement of agricultural goods, as animals were moved to markets and consumption sites while still alive (thus negating concerns about perishability) (Groot 2008a, 74–76), and products such as grain can be stored for longer periods of time. The latter is attested in the "Woerden 1" shipwreck (see also section 4.3.3.1), a pram which carried grain that had been stored for at least a year before being moved (Pals and Hakbijl 1992, 295).

4.3 Transport modes

In the same way that people and goods in the modern era can move and be moved through various modes of transportation (e.g. on foot, bicycle, car, truck, train), the population inhabiting the Dutch part of the Roman *limes* also had multiple modes of transportation available to them. The following sections are dedicated to exploring the literature available on modes of transportation in the past, whenever possible for the Roman Period in the Netherlands in particular, and properties of those modes such as range, speed and load capacity. The final section will provide a summary of the gathered data, in order to use this information for further modelling and analysis of transport in the Dutch part of the Roman *limes*.

4.3.1 Foot travel

The first and most obvious form of transport is movement on foot. Walking can be considered the original form of transport for anatomically modern humans, and has therefore been given substantial attention both within and outside archaeological research. A significant part of the literature that is used in archaeology stems from physiological research, where researchers are mostly interested in measuring energy expenditure while walking and introduce variables such as slope and terrain properties. Examples of these are Pandolf *et al.* (1976; 1977), Minetti *et al.* (2002), Bastien *et al.* (2005a) and Llobera and Sluckin (2007), who have published functions of energy expenditure against slope that are frequently used to calculate least-cost paths (i.e. optimal routes between points that aim to minimise a predefined cost). Similarly, functions that calculate walking speed rather than energy expenditure are also available, originally stemming from research on hiking, such as those by Naismith (1892; known as Naismith's rule), Langmuir (1984) and Tobler (1993). Research related to least-cost path analysis will be dealt with in more detail in Chapter 5. Instead, the following paragraphs will present other information available in the literature on walking as a mode of transportation.

When considering the local population inhabiting the Dutch river area, the majority of movement on foot would have been over relatively short distances, related to everyday activities and short movements to neighbouring settlements and perhaps local centres and market places, with longer distance travels happening only occasionally. Bakels (1978, 5–9) in her research on some settlements of the Neolithic Linear Band Ceramic culture uses the concept of 'site territory' and home range' to identify the area that would be exploited by the population in a settlement for everyday activities. The home range is similar but not identical to territory, as the latter has a connotation of exclusion, whereas home ranges of sites can overlap. Referring to a number of anthropological studies, she defines the territory of a site as a circle of approximately 2 hours in walking time, which would have been used for economic activities such as farming and animal herding. She defines the home range as a circle of approximately 6 hours of walking time, which is intended to equal a day's two-way travel, and could have been used for interaction with other settlements and procurement of rarer resources. The concept of home ranges of Bakels (1978) is closely related to site catchment studies, which aim to establish movement affordances related to agriculture and hunting-gathering (e.g. Vita-Finzi and Higgs 1970; Higgs and Vita-Finzi 1972; Gaffney and Stančič 1991).

There are a number of references on range of foot travel that are particular for the Roman Period (Table 4.2). Researchers in the ORBIS project (Fig. 4.5; Scheidel *et al.* 2012) have defined time costs for a number of transport modes based on a substantial set of literature. Related to travel on foot, they set a regular traveller at a velocity of 30 km/day. Assuming an average speed on flat terrain of 5 km/h (Tobler 1993), this corresponds roughly to 6 hours of travel. When treating the training of military recruits, Vegetius (*ERP*, 1.9) distinguishes between a regular pace of 20 Roman miles (29.6 km) and a full pace of 24 Roman miles (35.5 km), both completed in 5 summer hours while carrying 20.5 kg. These two exercises would be known as the *magnum iter* or forced march, while the *iustum iter* or regular march would be more in the range of 16 Roman miles (23.7 km; Kennedy 1965, 25). Chevallier (1972, 224–25) mentions a marching distance for Roman troops at 15 Roman miles (22.2 km) for long distances. Scheidel (2014, 12) sets an army on the march at 30 km/day, and furthermore the ORBIS model introduces short-term military march without baggage, that can reach up to 60 km/day (Scheidel *et al.* 2012). According to Laurence (1999, 82), a speed of 30 to 35 miles (i.e. 48-56 km) per day could even be considered normal, although this seems too high for regular marches and is indeed opposed by Scheidel (2014, 13) and Kolb (2000, 311), the latter stating that 20 km/day would be a more feasible long-term average.

Source	Distance	Time	Additional information
Chevallier 1972, 224–25	15 Roman miles (22.2 km)	Day	For long marching distances
Kennedy 1965, 25	16 Roman miles (23.6 km)	Day	Regular army march
Kolb 2000, 311	20 km	Day	Army march
Laurence 1999, 82	30-35 miles (48-56 km)	Day	Army march
Scheidel *et al.* 2012	30 km	Day	Regular traveller
Scheidel 2014, 12	30 km	Day	Army march
	60 km	Day	Short-term army march
Vegetius (*ERP*, 1.9)	20 Roman miles (29.6 km)	5 summer hours	Forced army march, regular pace, while carrying 20.5 kg
	24 Roman miles (35.5 km)	5 summer hours	Forced army march, full pace, while carrying 20.5 kg

Table 4.2. Sources on range per unit of time for foot travel in the Roman Period.

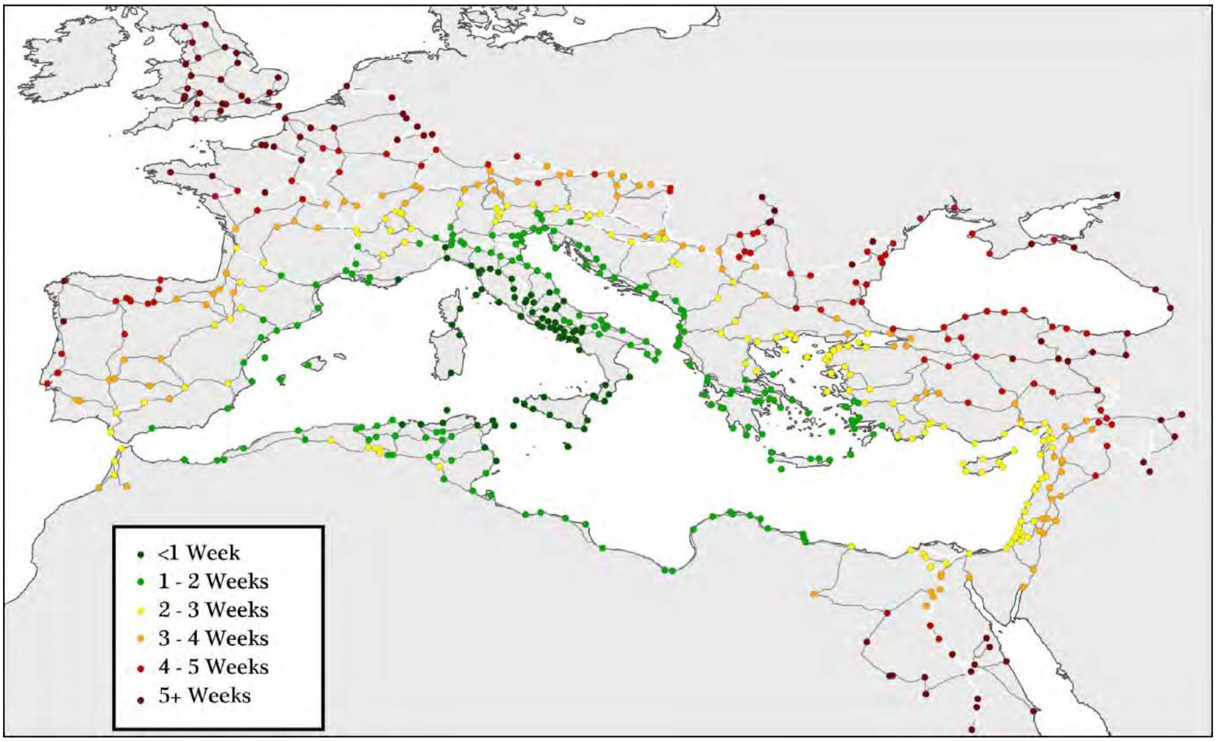


Figure 4.5. Travel time from Rome with the speed of a forced military march in the ORBIS model (from Scheidel et al. *2014, 17).*

Of course the distance that can be travelled within a certain time range, e.g. a day, is also dependent on the speed of travel. The travel times established in the ORBIS model are explicitly adapted for transport on the main roads, meaning the *viae publicae* (Scheidel *et al.* 2012), and this will be similar for many of the other estimations. The greatest impacts on speed of travel on the local scale, outside the corridors of the main roads, is usually found to be the natural environment in the form of relief (e.g. slope) and terrain properties. Relief is not a great factor in the Dutch river area, as the area is mostly flat, with the major elevation differences (in the range of tens of metres) occurring only around the edges of the research area. Terrain can be a major factor, and in studies that calculate time or energy expenditure while walking, terrain coefficients have been introduced to accommodate this factor (e.g. Soule and Goldman 1972; Brannan 1992; de Gruchy *et al.* 2017). Historic data on the effect of terrain on speed of travel in the Dutch *limes* zone is not available, as writers such as Caesar and Tacitus do not describe the natural landscape outside the various river courses of the Rhine-Meuse delta. Therefore we must rely on the aforementioned experimental data, possibly aided by historical data of younger time periods, to incorporate the influence of the environment when modelling transport. It must be kept in mind that these remain approximations, as the traversability of the terrain is dependent on a number of factors, including seasonality (see also section 4.2.3).

An important aspect to consider about foot transport, is that it is not only a way of moving people, but it can also involve the movement of goods. The common term for someone involved in the foot transport of goods is a porter, and there is historical evidence for porting being practiced in the Roman Period (Fig. 4.6). Indeed, the ORBIS model includes an option for the travel of porters, setting the range at 20 km/day (Scheidel *et al.* 2012). Unfortunately they do not indicate how much the porter would be carrying, yet this can greatly influence the speed of travel. Modern physiological studies suggest to set the maximum carried load at approximately one-third of a person's body weight, or 30 kg (Haisman 1988, 112–13), although it is dependent on how the weight is distributed over the body (Knapik *et al.* 1996, 213). This has also been shown for

Nepalese porters (Fig. 4.7), who are specialised in this profession and can routinely carry over 100% of their body weight primarily through head-supported loads, and do so across long distances in mountainous terrain (Bastien *et al.* 2005b, 1755). Of course we would not expect the population of the Dutch *limes* zone to achieve similar values, as Roman or local porters are likely not as professionalised as the Nepalese. Gregg (1988) in her study on Early Neolithic farmers indicates that porting was probably the main mode of transportation of goods in the Neolithic, as carts were not yet introduced at the time and there is no evidence for the use of beasts of burden. She sets the maximum porting capacity of wheat for men at 30 kg and for women at 20 kg (Gregg 1988, 161–62). In the Roman Period, porting would most likely only be relevant for local transport due to the presence of beasts of burden and carts, and would not have played a role in regional or intraregional transport, with the exclusion of Roman soldiers on the march. Specifically for the Roman military, estimates have been made of the weight of a soldier's marching pack (*sarcina*). Such estimates range between 30 pounds (13.6 kg) and 100 pounds (45.4 kg) (Roth 1999, 71–75), with the upper ones being close to two-thirds of a soldier's body weight, which is probably somewhat too high. Vegetius (*ERP*, 1.19) states that a Roman soldier must be accustomed to carrying 60 Roman pounds (19.7 kg), which is considered a more realistic average by historians (Phang 2008, 217).

Figure 4.6. Mosaic of a man porting a basket of vegetables (photo Bardo National Museum, Tunis).

Figure 4.7. Nepalese porter carrying roughly 100% of his body weight (from Bastien et al. *200*

4.3.2 Animal-based transport

Animals can also be involved in the movement of goods, either as pack animals or draught animals. Trajan's Column for example shows the use of mules (the offspring of a male donkey and a female horse) pulling two-wheeled carts carrying artillery for the Roman army (Fig. 4.8), and oxen (male castrated cattle) and mules drawing carts to deliver supplies to a fort in Dacia (Fig. 4.9; Lehmann-Hartleben 1926). Carts could be two- and four-wheeled and were also in use in northwestern Europe, as is evidenced by their depiction on funerary steles (Fig. 4.10; Adam *et al.* 2002). The Roman army was very dependent on the use of mules and oxen for their baggage trains, and the loss of animals would be a great concern to any Roman general (Southern 2007, 222–24). Regarding mules, a distinction can be made between female mules that are primarily used for drawing carts, and male mules, that are mostly employed as pack animals (Adams 1993). Besides oxen and mules, horses could also have been used for the transport of goods, primarily as pack animals and not very often as draught animals. The traditional view was that the throat-girth collar, similar to the yoke for oxen, hindered the horse's breathing and reduced its pulling power. The modern horse collar, which greatly improved the horse's draught capacity, would not be introduced until well after the Roman Period (Chamberlin 2006, 109). However, experiments on ancient harnessing methods have shown that claim to be false, as the horse would pull the weight from its chest rather than its throat, and so would not lose any traction (Raepsaet 1979). The more likely explanation for not using horses as draught animals is that oxen are cheaper, plentiful, can be yoked together and can be fed more efficiently (Greene 1986, 39).

Figure 4.8. Depiction of mules pulling a two-wheeled artillery cart on Trajan's Column (photo Matthias Kabel).

Figure 4.9. Depiction of oxen and mules pulling two-wheeled supply carts on Trajan's Column (photo Matthias Kabel).

Although mules were probably preferred by the Roman army, donkeys (asses) have been in use as well and could replace mules where they were not available. Particularly in the Mediterranean areas, the donkey was the most common transporter of goods among the non-military population (Roth 1999, 205). However, donkeys are not very suited to the temperate climate of northwest Europe, making it unlikely for them to be in common use in the Dutch *limes* zone. For the same reason, mule production farms were also exclusively located in the Mediterranean areas, and thus mules could only be used in the Dutch *limes* zone when they were imported, likely placing more emphasis on the use of oxen and horses (Stallibrass and Thomas 2008, 157). Both donkeys and mules are only rarely reported in Roman sites in the Dutch river area (e.g. Krist 2002; Waasdorp 2012 for mules), but this is also a consequence of the difficulty of discerning between bones of equine species, meaning that a systematic survey of horse bone may reveal a higher presence of donkeys and mules (Groot 2008a, 197). Other pack or draught animals that were available in the Roman Empire are elephants and camels, the latter of which were certainly in common use in the Near East and North Africa (Roth 1999, 207), but in the Dutch

Figure 4.10. Depiction of mules pulling a four-wheeled cart transporting bales on a 4th century funerary stele from the castrum *of Strasbourg (photo Musée archéologique, Strasbourg).*

limes zone such exotic animals have not played a role.

For the aforementioned reasons the following sections will focus on the animals that are most likely to be involved in the transport of goods in the Dutch part of the Roman *limes*, namely horses as pack animals, and mules and oxen as both pack and draught animals. Estimates of the speed, endurance and load capacity of these animals vary widely and are of course interdependent as well as dependent on a number of other factors such as terrain or climate. To make things more complicated, both Roman sources and studies by historians are not always in accordance, for example by being unclear if the weight of a cart is included or excluded from the load transported by draught animals. Furthermore, estimates of maximum pack loads vary, and the distribution of the load, which is also dependent on the type of good that is transported, is mostly not taken into account but undoubtedly important.

4.3.2.1 Horses

Related to horses, the 4th century Theodosian Code states that the maximum load of horses is 30 Roman pounds (9.9 kg) plus the weight of the rider. This must exclude the saddle and bridle, as these limitations where adjusted a few decades later to 35 Roman pounds (11.5 kg) plus the weight of the saddle of 60 Roman pounds (19.7 kg) and the rider (Hyland 1990, 256–57). In comparison, modern horses of similar stature to the ones that were used by the Roman army typically carry 18-22.5 kg in addition to a rider and saddle (Hyland 1990, 256). For the baggage train of Hannibal's army, Shean (1996, 170) estimates the total maximum load to be 400 pounds (181 kg), but also mentions that other authors suggest a lower maximum weight of 200 pounds (90.7 kg). The latter seems more reasonable as it is more in line with the earlier mentioned estimates of pack load plus saddle and rider. Goldsworthy (1996, 293) similarly sets the maximum weight at 200 pounds, separated between 48 pounds (21.8 kg) for the harness and pack, and 152 pounds (68.9 kg) for the transported load. These pack horses could travel at a speed of 3-3.5 miles/h (4.8-5.6 km/h). Goe and McDowell (1980) in their review on animal traction in non-industrialised countries find that the average pack load of horses is between 40 and 75 kg with absolute maximum pack loads being between 55 and 95 kg, depending on the weight of the horse. Considering their stature, the horses of the Roman Period should probably be found on the lower end of this spectrum. Under these pack load conditions they would be able maintain a speed of 5.6 km/h for 6 to 8 hours (Goe and McDowell 1980, 39), amounting to a total range of 34 to 45 km/day. According to the ORBIS model a horse with rider on a routine journey could travel up to 56 km/day. In a horse relay system, which would only really be viable on the main roads due to the need for transfer stations, a rider could even cover a distance of 250 km/day (Scheidel *et al.* 2012) (Table 4.3).

Source	Distance	Time	Load	Additional information
Goe and McDowell 1980	5.6 km	Hour, for 6-8 hours	40-75 kg	Typical pack load
	56 km		55-95 kg	Maximum pack load
Goldsworthy 1996, 293	3-3.5 miles (4.8-5.6 km)	Hour	200 pounds (90.7 kg)	48 pounds for harness and pack, 152 pounds for transported load
Hyland 1990, 256–57			30-35 Roman pounds (9.9-11.5 kg)	Excluding saddle (60 Roman pounds, 19.7 kg) and rider; Theodosian Code
			18-22.5 kg	Modern horses of Roman Period stature, excluding saddle and rider
Scheidel *et al.* 2012	56 km	Day		Horse with rider
	250 km	Day		Horse relay
Shean 1996, 170			400 pounds (181 kg)	
			200 pounds (90.7 kg)	Suggested by other authors

Table 4.3. Sources on speed (or range per unit of time) and load for horse transport, primarily in the Roman Period.

4.3.2.2 Mules

Mules are tougher and more tolerant than horses and sturdier and more obedient than donkeys, making them popular animals in Roman transportation (Greene 1986, 39). Roman sources suggest that mules (and donkeys) were more popular as pack animals for the transport of grain than horses and oxen, at least in Egypt and Sicily (Yeo 1946, 224–25). Estimates of the maximum pack load of mules in the Roman Period vary widely, roughly between 72 and 135 kg (Roth 1999, 206). The only direct source, the 4th century Diocletian's Price Edict, gives a figure of 300 Roman pounds (91 kg) for a mule's pack, although this must be seen as a legal maximum load rather than an absolute one (Roth 1999, 206). For Caesar's army, Labisch (1975, 83) sets a mule's pack load at 100 kg. White (1984, 129) estimates a load of pack mules between 90 and 136 kg. In his study of the Roman army, Goldsworthy (1996, 293) estimates the maximum pack load at 200 pounds (90.7 kg), separated between 48 pounds (21.8 kg) for the harness and pack and 152 pounds (68.9 kg) for the actual transported load. These pack mules would travel at a speed of 3-3.5 miles/h (4.8-5.6 km/h). Shean (1996, 170) in his study of Hannibal's army sets the maximum pack load of mules at 300 pounds (136 kg), and their range at 49¾ miles/day (80 km). Goe and McDowell give two different values for mules: from a literature review they deduce that mules can travel 40 km/day for 30 days in succession while carrying 112 kg (Goe and McDowell 1980, 17), while giving their own values of a speed of 7.2 km/h for 6-8 hours (giving them a maximum range of 58 km/day), carrying on average a load between 34 and 82 kg, up to a maximum of 115 kg (Goe and McDowell 1980, 39). In the ORBIS model, Scheidel *et al.* (2012) set the maximum range of moderately loaded mules at 30 km/day and 'fully loaded' mules at 20 km/day, but do not specify what constitutes a 'full load'. Kolb (2000, 310) proposes a maximum range for pack mules of 30 km/day. During World War I pack mules were found to typically carry up to 200 pounds (90.7 kg) (Landels 1978, 171–73) and travelled 49 miles (79 km) per day. One can only assume the driver of these animals is not travelling on foot, as a person on foot would not be able to cover that same distance. The large difference between all aforementioned ranges may be explained by this role of the driver: in the Roman Period the driver guiding pack animals would often be on foot, and thus the range and speed of the animals are bounded by that of the driver. In his study on the grain supply of ancient Rome, Rickman (1980, 14) explicitly takes this into account and sets the maximum speed of pack mules at 3-4 miles/h (4.8-6.4 km/h), 'at the walking speed of men' (Table 4.4).

Source	Distance	Time	Load	Additional information
Pack mules				
Goe and McDowell 1980	40 km	Day, for 30 days	112 kg	Literature review
	7.2 km	Hour, for 6-8 hours	34-82 kg, max. 115 kg	Modern mules
Goldsworthy 1996, 293	3-3.5 miles (4.8-5.6 km)	Hour	200 pounds (90.7 kg)	48 pounds for harness and pack, 152 pounds for transported load
Kolb 2000, 310	30 km	Day		
Labisch 1975, 83			100 kg	
Landels 1978, 171-73	49 miles (79 km)	Day		World War I
Rickman 1980, 14	3-4 miles (4.8-6.4 km)	Hour		
Roth 1999, 206			72-135 kg	Variety of estimates
			300 Roman pounds (91 kg)	Diocletian's Price Edict
Scheidel *et al.* 2012	30 km	Day		Moderate load
	20 km	Day		Full load
Shean 1996, 170	49¾ miles (80 km)	Day	300 pounds (136 kg)	
White 1984, 129			90-136 kg	
Mule-carts				
Bachrach 1993, 717	30 km	Day	500 kg	Early Medieval Period
Laurence 1998, 218	50 miles (80 km)	Day	400 kg	American Mid-West

Table 4.4. Sources on speed (or range per unit of time) and load for mule transport, primarily in the Roman Period.

Besides the use as pack animals, mules could (less commonly, cf. Shean 1996, 170) also be used as draught animals, pulling a two-wheeled cart or a four-wheeled wagon and likely (but not necessarily) operating such a vehicle in pairs. Unfortunately, many authors are unclear on the exact configuration they are describing when they estimate load and travel speed of draught animals. When thinking about the exact weights a mule can pull, it is relevant to first get an idea of what the specifics of the vehicle itself are. Goe and McDowell (1980, 7) provide some parameters on carts in their review of animal traction in non-industrial countries. The weight of iron-rimmed carts is divided into 373 kg for the cart itself and a potential 933 kg for the load (total 1306 kg). The required draught for this cart on a dirt road is 27 kgf (kilogram-force; a non-SI[1] unit of force that is traditionally used for draught power), on a ploughed field 178 kgf. A wooden-wheeled cart weighs 252 kg and carries a load of 597 kg (total 849 kg), requiring a draught of 36 kgf on a dirt road and 127 kgf on a ploughed field.

The draught requirements can be related to the draught power of animals: mules for example can develop a draught power of 50-60 kgf at a normal pace (4 km/h), up to 96 kgf at a low pace (2.4 km/h), developing a power of 0.7-0.9 hp (horsepower; a non-SI unit of energy consumed per unit time equal to 735.5 W) (Goe and McDowell 1980, 17, 38). The higher values are for modern mules, and likely do not reflect the power a mule could generate in the Roman Period. A single mule can thus not pull a cart across non-compacted terrains such as a ploughed field as the amount of draught generated is too low. Mules working in teams might be able to generate enough draught, although the relation between draught and number of animals is not linear: according to Goe and

[1] *Système international d'unités* – International System of Units; the SI unit of force is N (Newton)

McDowell (Goe and McDowell 1980, 13) the efficiency loss of a pair of animals is 7.5% and of four animals 22%, while Raepsaet (2002, 26) states that two animals work at 186% (loss of 7%) and four animals at 308% (loss of 23%). Metrics on draught and velocity can also be used in a more quantitative calculations, which will be further discussed in the chapter on modelling transport, section 5.3.3.

Some more general estimates for loads and ranges of mule-carts are also available. For the Early Medieval period, Bachrach (1993, 717) gives a range of 30 km/day for mule-carts with a load of 500 kg. According to Laurence (1998, 218) mules in the American Mid-West could pull 400 kg cart loads for 50 miles (80 km)/day. The above values for load imply that they do not include the weight of the cart itself, although that remains uncertain as long as it is not explicitly stated. Mule-carts in the ORBIS model travel 30 km/day with an unknown load (Scheidel *et al.* 2012) (Table 4.4).

4.3.2.3 Oxen

Most estimates of the speed and load capacities of oxen are based on ox-carts, even though oxen can also be employed as pack animals, similarly to horses and mules. Again, authors often do not explicitly state whether they are referring to an ox-cart pulled by a team of oxen or a single ox, which can make a large difference in terms of an ox-carts capacity. Since there is material evidence of the use of yokes (Nicolay 2007 250–56), the use of pairs of oxen was possible in the research area.

Oxen are slower animals and work shorter hours, but can generally carry or pull heavier loads. As pack animals in Hannibal's army, Shean (1996, 170) sets the pace of an ox at 2 miles/h (3.2 km/h). Goldsworthy (1996, 293) estimates a pace of 2-2.5 miles/h (3.2-4.0 km/h), while carrying a load of 160-200 pounds (73-91 kg), which is separated between 30-60 pounds (14-27 kg) for the harness and pack and a further 100-170 pounds (45-77 kg) for the transported load. According to White (1984, 129) the total load can even weigh up to 400 pounds (181 kg). In their review on animal traction in non-industrial countries, Goe and McDowell (1980, 40) give values for an average load of 30-90 kg, with an absolute maximum load of 175 kg, while maintaining a pace of 3.5 km/h. This maximum load is only possible for the largest and heaviest of oxen in modern times, which likely does not reflect the average stature of oxen in the Roman period (Table 4.5).

For oxen as draught animals, Junkelmann (1997, 62) proposes a maximum speed of 3 km/h for a maximum of 5 hours, arriving at a total range of 15 km. This figure of 15 km/day is also given by Bachrach (1993, 717), and a similar figure of 12 km/day is suggested by Kolb (2000, 310) and Scheidel *et al.* (2012). In contrast, Roth (1999, 211) gives a range of 19-24 km/day for ox-trains in the American Mid-West. Rickman (1980, 13) only mentions an average speed of 2 miles/h (3.2 km/h). Almost none of these sources associate their given speed or range of travel with a certain pulled load directly, although this is undoubtedly important. The 4th century Theodosian Code and Diocletian's Price Edict provide values of 1075 Roman pounds (352 kg) and 1200 Roman pounds (393 kg) respectively, although these are not absolute maximum values (Roth 1999, 211). More typically, the transported load would weigh 500-550 kg (Labisch 1975, 43; White 1984, 132; Bachrach 1993, 717) for two-wheeled carts, and 650 kg for the occasional four-wheeled wagon (Bachrach 1993, 717). Assuming this does not include the weight of the cart itself, these values correspond quite well with the load values for wooden-wheeled carts by Goe and McDowell (1980, 7), who put the weight of the cart itself at 252 kg and the carried load at 597 kg, for a total of 849 kg. This cart would require a draught of 36 kgf on a dirt road and 127 kgf on a non-compacted surface such as a ploughed field. Depending on its size and strength, one ox would be able to generate a draught of 21-90 kgf at a speed of 4.0 km/h and a draught of 30-129 kgf at a speed of

2.2 km/h, at 0.3-1.1 hp (Goe and McDowell 1980, 38). However, the higher values of draught are for modern oxen and likely do not reflect the likely smaller oxen of the Roman Period. A fully-loaded cart would thus almost always require a pair of oxen to move it about (Table 4.5).

Source	Distance	Time	Load	Additional information
Pack oxen				
Goe and McDowell 1980	3.5 km	Hour	30-90 kg, max. 175 kg	Modern oxen
Goldsworthy 1996, 293	2-2.5 miles (3.2-4.0 km)	Hour	160-200 pounds (73-91 kg)	30-60 pounds for harness and pack, 100-170 pounds for transported load
Shean 1996, 170	2 miles (3.2 km)	Hour		
White 1984, 129			400 pounds (181 kg)	
Ox-carts				
Bachrach 1993, 717	15 km	Day	500-550 kg	Two-wheeled cart
	15 km	Day	650 kg	Four-wheeled wagon
Goe and McDowell 1980			849 kg	Modern wooden cart, 252 kg for cart and 597 kg for load
Junkelmann 1997, 62	3 km	Hour, for 5 hours		
Kolb 2000, 310	12 km	Day		
Labisch 1975, 43			500-550 kg	Two-wheeled cart
Rickman 1980, 13	2 miles (3.2 km)	Hour		
Roth 1999, 211	19-24 km	Day		American Mid-West
			1075-1200 Roman pounds (352-393 kg)	Diocletian's Price Edict
Scheidel *et al.* 2012	12 km	Day		
White 1984, 132			500-550 kg	Two-wheeled cart

Table 4.5. Sources on speed (or range per unit of time) and load for ox transport, primarily in the Roman Period.

4.3.3 Water-based transport

Water-based transport is a sometimes overlooked part of transport research. In transport systems of Roman Italy, land transport largely dominates over river transport, perhaps with the exception of the Tiber river, and is in turn dominated by sea transport. On the local to regional scale, similarly to the scale of the Dutch river area in which the sea is peripheral, most transport movements in Roman Italy would thus have occurred over land. However, the situation of the Mediterranean countries poorly reflects that of the areas north of the Alps such as Gaul and Germania, where rivers can often be navigated throughout the year and form natural corridors of movement from deep inside the hinterland to the sea (Laurence 1999). When it concerns the transport of commercial goods, Roth (1999, 196) states that the Romans preferred rivers to roads whenever possible. For the Dutch part of the Roman Lower Rhine *limes* this may be reflected in the fact that the first evidence for road infrastructure dates almost a century after the establishment of the Roman *castella* along the Rhine (Van der Heijden 2011, 33; not true for the German part of the Lower Rhine *limes*, and an Early Roman precursor can also not be entirely ruled out). This means that the supra-regional provisioning of these military garrisons likely happened primarily over water (Junkelmann 1997, 59). The following sections will deal with water-based transport on two levels: firstly the level of large-scale, mostly supraregional transport, and secondly the level of local and regional scale water-based transport.

4.3.3.1 Prams, punters and galleys

Due to the suitable conditions for the preservation of wood, a substantial amount of archaeological evidence for shipping is available in the Dutch river area. This section focusses on ships that would primarily have been used for transport over large distances, i.e. supraregional transport. A number of Roman ships have been found in the Netherlands that fall into this category, including prams (Dutch: *praam*/*platbodem*; Fig. 4.11), punters (Fig. 4.12) and galleys (Dutch: *gallei*; Fig. 4.13), and some have been intensively researched. In terms of transport, the most interesting ships are the prams of the so-called Zwammerdam type (Fig 4.11), which are shallow-draught flat-bottomed river ships named after a series of ships of this type that were found in the 1970s in the river bed of the Old Rhine near Zwammerdam (De Weerd 1988; Bockius 2000). Besides the three prams that were found there, further along the Roman course of the Rhine at least three more were discovered in Woerden (Haalebos 1986; Blom and Vos 2008), and at least two more in De Meern (Jansma and Morel 2007; De Groot and Morel 2007; Langeveld *et al.* 2010a). A third ship in De Meern could not be proven with certainty due to the limited amount of evidence (Aarts 2012), and a possible fourth ship in Woerden was already found in 1576 and is only known from written sources (Brouwers *et al.* 2013, 24). Elsewhere in the Dutch river area, one pram of the Zwammerdam type was found in Druten along the Waal river (Hulst and Lehmann 1974), and one near Kapel Avezaath along the Linge river (De Weerd 1988; Bockius 2000).

Figure 4.11. The "De Meern 1" shipwreck on display in Castellum Hoge Woerd, De Meern (photo René Voorburg).

The prams found in the Dutch river area are all of relatively standard size, between 20 and 30 m long and 3 to 4.5 m wide. De Weerd (1988) has shown that Zwammerdam type ships were constructed using the Roman foot (a unit of 29.6 cm) for dimensions. For example, the ship "Woerden 1" is 29.6 m (100 Roman feet) long and 3 m (10 Roman feet) wide. This is a relatively slim ship with a length-width ratio of 10:1; most prams that have been discovered in the Netherlands actually have a length-width ratio between 6.3:1 and 7.7:1. Most prams have a board height of around 1 m, and roughly half of that would be below water. This allowed prams to sail on the Rhine and other rivers in the Dutch river area, assuming a depth of the summer bed of 2 m (Jansma and Morel 2007, 152). The water depth of the main river bed would be greater in fall and spring due to a higher discharge (from rainfall and snowmelt), but this would not have been beneficial for shipping as the increased depth and speed of flow would have made these flat-bottomed prams unstable, and the shallowness of the winter bed in contrast to the summer bed would have made navigation treacherous (Jansma and Morel 2007, 152). Shipping would thus have been a seasonal venture and would not have been possible year-round. This may also be the explanation for the presence of *nautae* of Tungrian origin in Vechten (see also Fig. 4.4): after delivering goods (possibly cereals; Roymans 1996a, 82) from the Tungrian *civitas*, they had to wait out the winter before making the return journey.

It has sometimes been suggested that these prams were used for a one-off transport of goods, particularly for building material such as wood and stone, in a downstream direction (Hulst and Lehmann 1974, 20–21; Haalebos 1997, 83–84; Brouwers *et al.* 2013, 20). The ships would be constructed in the source area of goods, such as Flanders, the Ardennes or the German Rhineland, and once the goods were delivered in the Dutch river area, the ships would be deconstructed for building material, or intentionally sunk to function as makeshift quay reinforcements (the latter of which has been proven for some of the ships found). However, recent research has found that at least the "Woerden 7" ship was constructed with wood from the Ardennes as well as the Dutch Rhine-Meuse delta, suggesting that the wood from the Ardennes was imported but that construction took place locally (Brouwers *et al.* 2013, 19). Similarly, for the "De Meern 4" ship it is suggested that it was constructed in a local shipyard, possibly under auspices of Roman (military) officials, based on the mix of Roman and local construction techniques and the generally poor execution of those techniques (De Groot and Morel 2007, 63–64). That these prams were used for more than one trip is also supported by the relatively long lifespans of some of the ships found, such as the "Zwammerdam 4" vessel which was in service for roughly eighty years (De Weerd 1988, 148).

Since prams were used for a longer period of time, navigation must have been possible in both the upstream and downstream direction. The propulsion of prams was likely performed through a combination of sailing and pulling. A number of ships were found to have a hole for a light mast around a quarter down the length of the ship, giving the ships limited to good sailing capabilities, depending on the type of sail and rigging used (Jansma and Morel 2007, 160–64). Alternatively, ships could have been pulled from the shore, which has been shown to be practiced in the Roman Period (Bockius 2000, 461–64) and for which the light mast of the found prams would have been sufficient as a lever. Pulling a pram in an upstream direction would require a pulling force of approximately 250 N, which can be easily managed by two persons or one draught animal. So-called tow paths have not been archaeologically attested in the Dutch river area, but the assumed lack of trees particularly on the levees of the Rhine and the relatively good traversability of the terrain of the levee makes pulling a possible, though perhaps less desirable, option for propulsion (Jansma and Morel 2007, 169–70). A final option for propulsion is through rowing, which has been attested at least on the "Woerden 7" ship. This pram had place for at least twelve rowers, although a mast was also present. Rowing was likely only used as an extra aid in turning, berthing, and propulsion on calm water (Brouwers *et al.* 2013, 19).

The speed and range of transport over water is of course very dependent on the direction of travel, and can be further influenced by aspects such as the season. The flow of the Rhine during the summer is estimated to be 0.8-1.0 m/s (Hesselink *et al.* 2006) and this has a noticeable impact on travel speed. In the downstream direction, the pram could choose to either sail down the river without extra propulsion, moving at the average pace of 0.9 m/s (3.2 km/h), or through extra propulsion increase its speed by 1.4 m/s. The latter would result in a total downstream speed of 2.3 m/s (8.3 km/h), giving prams a downstream range of approximately 60-90 km/day. In an upstream direction this is markedly different, as by means of the regular average propulsion of 1.4 m/s, the pram would only be moving upriver at a speed of 0.5 m/s (1.8 km/h) relative to the shore. This would also be the speed using pulling as method of propulsion. The distance that then could be covered in a day amounts to 15-20 km, perhaps occasionally 25 km (Jansma and Morel 2007, 158).

The traditional ideas regarding the transported load of prams in the Dutch river area is that they were primarily used for the downstream transport of heavy construction material such as wood and stone (Bockius 2000, 478). Evidence for this are the finds of slate in the "Zwammerdam 2" ship and brick dust in the "Zwammerdam 4" ship. However, the fact that ships have been used for longer periods of time and thus would have travelled in both up- and downstream direction has already partly proven that the aforementioned hypothesis was not always true. More detailed calculations of the actual load capacities of ships have since been done on a number of prams found in the Dutch river area. For the "De Meern 1" ship the average load pressure was found to be 500 kg/m², for a total maximum load of 14,000 kg. The relatively low load pressure is an indication that this ship was designed to be primarily used for the transport of light loads such as merchandise, hay, straw and so on. It was not impossible to carry heavy loads, but in such cases the space available to carry loads would be used quite inefficiently. Calculations for the "Zwammerdam 2" and the "Mainz 6" (a pram found along the Rhine in Mainz, Germany) have found similar average load pressures. The former had a total maximum load of 11,000 kg, while the latter had a maximum load of 62,000 kg, a figure which is larger mostly due to the ship's greater size (approximately 40×5 m) rather than a higher average load pressure. Only the "Woerden 1" was calculated to be able to carry average load pressures of 1,600 kg/m², for a total maximum load of 52,000 kg, making it the only pram proven to be designed to carry heavy loads such as construction materials (Jansma and Morel 2007, 156–58). However, at the time the "Woerden 1" ship sank, it was carrying grain from the loess area in Belgium that was probably destined for Britain (Pals and Hakbijl 1992, 293–94).

One notably different transport ship that was found in the Dutch river area is the "De Meern 4". It is the first and so far only find of a so-called punter ship from the Roman Period in the Dutch river area. Punters are small flat-bottomed and lancet-shaped ships, not unlike punters that have been used throughout the Medieval period in the Dutch river area and are still in use for example in the Dutch town of Giethoorn today (Figure 4.12). The punter measured 9×1 m, which is remarkably slim in comparison to Medieval punters and the single other punter dated to the Roman Period, the "Corte Cavanella II" from Italy. It might have been used for transporting relatively heavy loads, based on its similarity to so-called 'bok' type ships, which is a modern definition for a subgroup of punters designed to carry heavier loads in comparison to traditional punters. However, exact calculations on load capacity have not been made. Its method of propulsion is also unknown: even though the modern name 'punter' suggests 'punting' (i.e. poling) as the method of propulsion, regular sailing or pulling was also possible if there was a mast present (Aarts 2012, 217–36).

Figure 4.12. Typical punter-type ship (photo Zuiderzeemuseum, Enkhuizen).

A final type of ship that would have been used primarily over longer distances is the galley, a long and slim military ship propelled by rowers. The galleys that were active on the rivers of Gaul and Germania were smaller than their Mediterranean counterparts, as attested by a number of these ships that have been found in Oberstimm and Mainz in Germany (Fig. 4.13). The only non-fragmented find of a galley in the Dutch river area is the "Vechten" ship, discovered in the late 19th century. It measured 12×3×1.5 m and had place for approximately twenty rowers. Ship fragments that probably belonged to galleys have furthermore been found in Zwammerdam, Woerden and Velsen, although they were only recognised as such based on the 'Mediterranean' construction techniques that were customarily employed for galleys (Brouwers *et al.* 2013, 21).

Figure 4.13. Reconstruction of the "Mainz 3" galley in the Museum für antike Schifffahrt, Mainz (photo Marco Prins).

4.3.3.2 Dugouts

Dugouts, also known as dugout boats, dugout canoes, logboats or *Einbaumen* (German), are a type of watercraft that has been used at least since the Mesolithic (e.g. the 8th millenium BC "canoe of Pesse"; Van Zeist 1957), and that has morphologically and technologically not substantially changed since (Fig. 4.14). For this reason they may be seen as the continuation of the local tradition of sailing, and the main representative of water-based transport on the local scale. They are often neglected in studies on Roman water-based transport, perhaps due to the larger transport capacity and generally greater appeal of the prams that were simultaneously active in the Dutch river area. Dugouts are by definition constructed from a single tree that has been hollowed, usually through burning but also through chopping. The board of the dugout may have been heightened with additional planks, and the sides of the boat were always reinforced with additional knees to maintain the boat's structural integrity. From the Roman Period, eight dugouts were discovered in the Dutch river area: two in de Meern (unpublished, found together with the "De Meern 1" pram; Jansma and Morel 2007), two in Woerden (Beunder 1988) and three in Zwammerdam (De Weerd and Haalebos 1973; De Weerd 1988; Koehler 1997), all along the Rhine, and a final one near the Meuse estuary in Alblasserdam (unpublished, see also Van der Heide 1974; Moerman and Wilbers 2016).

The eight Roman Period dugouts found in the Dutch river area have not all been equally preserved: sometimes only fragments remained. The largest dugout, the "Woerden 3", measured 12×1.2 m (Brouwers *et al.* 2013, 24). Most dugouts were smaller, around 6-7 m long, although due to the fragmented nature of the evidence no 'standard' size dugout can be defined. Furthermore, it is very likely that there was no standard size dugout, as the size is very dependent on the size of the tree available.

Figure 4.14. Reconstruction of a Roman Period dugoat in the National Museum of Slovenia, Ljubljana (photo Daniel Thornton).

The frequently used term 'dugout canoe' implies paddling as the means of propulsion, although this is not necessarily the case, and often the manner of propulsion cannot be established with certainty simply due to the lack of evidence (Maarleveld 2008, 9–11). However, the "Zwammerdam 3" boat, a dugout of 10.66 m in length, has a hole for a mast in the centre of the boat as well as traces of wear that indicate the use of oars. This dugout may thus have been moved through a combination of sailing, pulling and rowing (Maarleveld 2008, 10). Meanwhile, due to the lack of evidence, paddling could not be proven as a method of propulsion, making 'canoe' a rather unfit descriptive term for this boat.

No further quantitative calculations have been made on the Roman Period dugouts of the Dutch river area. More research has been done on dugouts in the British isles. The experimental "Daire" dugout (Fig. 4.15), based on five (non-Roman) dugouts from Ireland, measured 5×0.65 m and could safely carry up to 430 kg on calm water (Gregory 1997, 227). This figure includes both passengers and transported goods. Gregory (1997, 252) also calculated the maximum load capacities for a number of other archaeologically attested Irish and Scottish dugouts. Most boats measured between 3 and 4 m in length and could have carried between 600 and 750 kg, including both passengers and transported goods. Their capacities are higher than that of the "Daire" dugout, primarily due to the latter's smaller width. One exceptionally long dugout, the "Lurgan" at 13.6 m in length, could have carried around 7,400 kg. Some decades ago, McGrail (1978) made an inventory of 179 dugouts in England and Wales and calculated load capacities for a total of 24 hypothetically reconstructed boats. These dugouts varied in length between 2 and almost 15 m, and had maximum load capacities between 100 and over 11,000 kg (assuming an average person weight of 70 kg, which he separates from his calculation of loads). The data of McGrail (1978) have been plotted in Figure 4.16 along with those of Gregory (1997), giving a rough idea of the relation between length and load capacity. The actual causal relation of load capacity is of course with volume and board height rather than length, but these figures are rarer to come by both for the British Isles' dugouts as well as for the Roman period dugouts of the Dutch river area. Estimating from the figures for British Isles' dugouts, the "Woerden 3" boat would have had a maximum load capacity of approximately 4,500 kg and the boats of 6-7 m would have probably been able to carry around 1,000-1,200 kg, including both passengers and goods. It must be noted that these are absolute maximum load capacities in calm water: actual loads would generally have been lower, especially under less than perfect weather and water conditions.

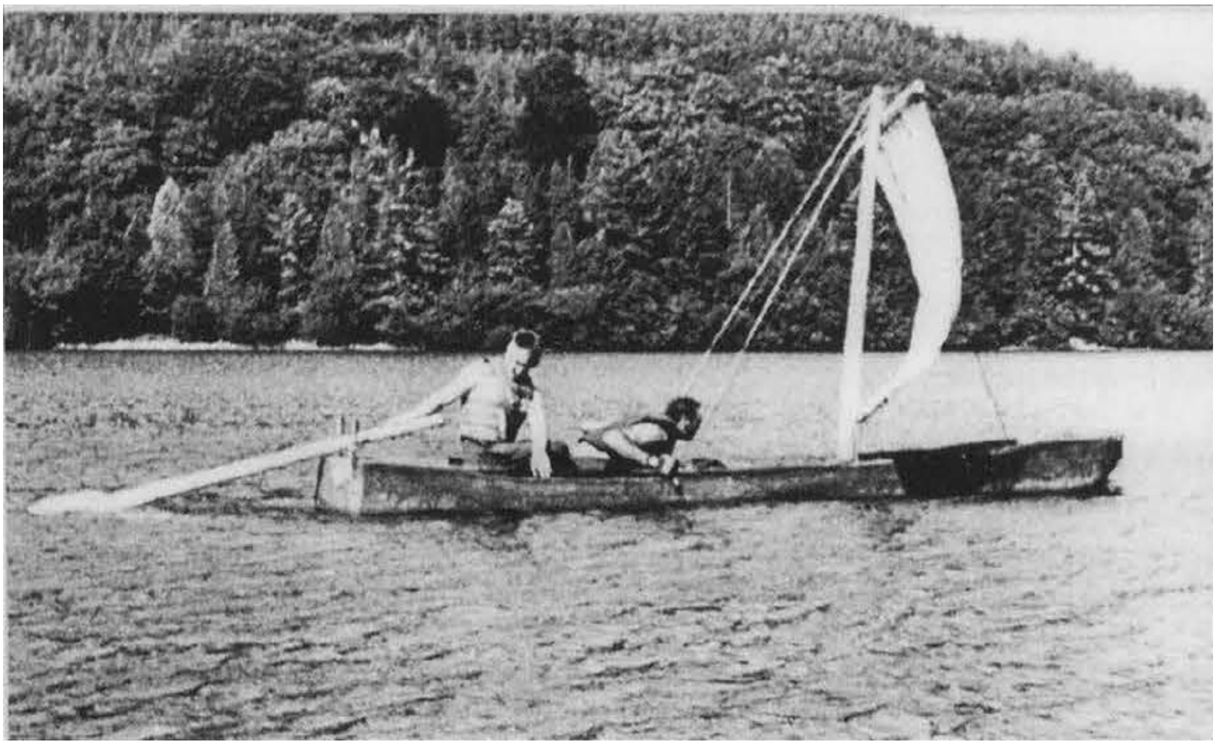


Figure 4.15. The experimental dugout "Daire" being subjected to tests with sailing as the method of propulsion (from Gregory 1997, 19).

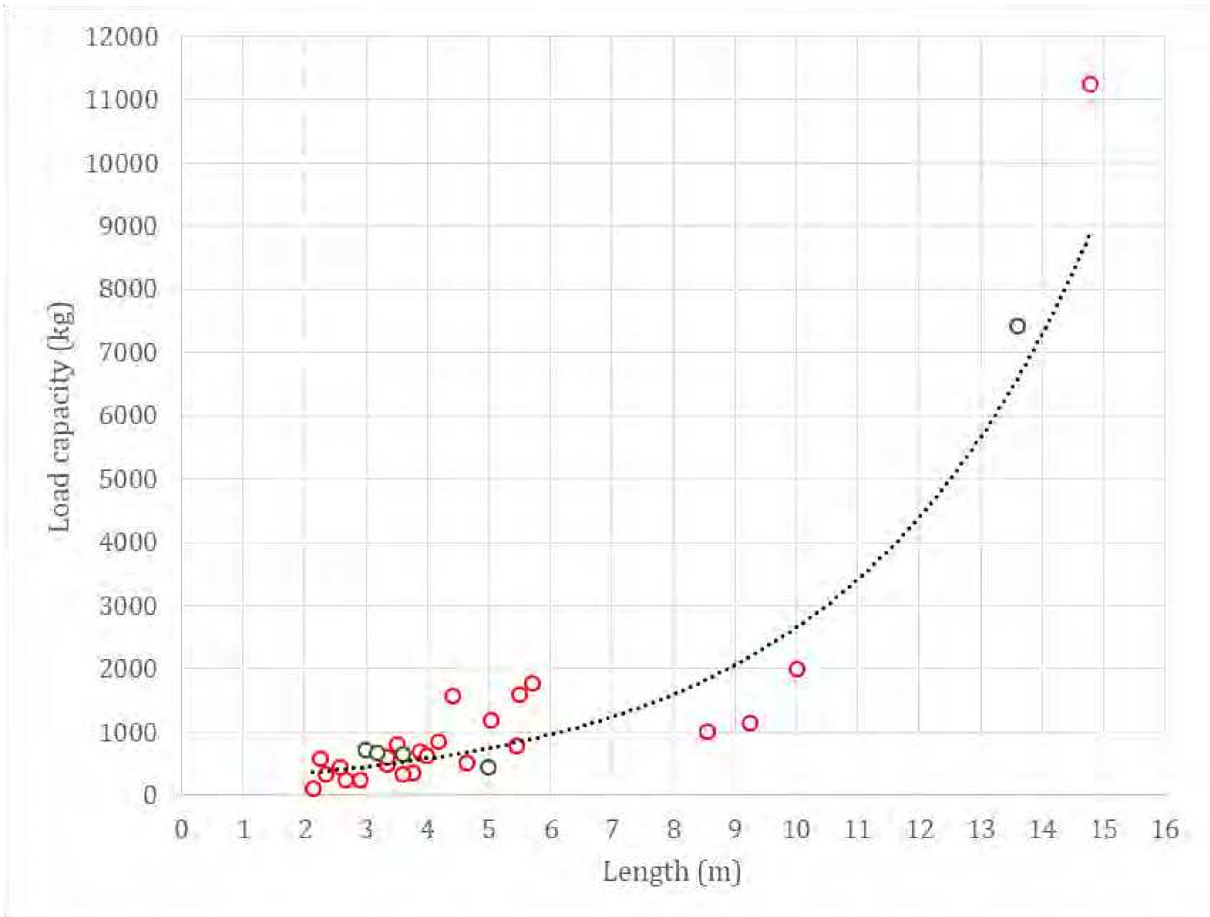


Figure 4.16. Relation between length and load capacity for English/Welsh (red) and Irish/Scottish (green) logboats, based on data from McGrail (1978) and Gregory (1997).

On the topic of speed, the "Daire" dugout was tested with various methods of propulsion and loads on a lake (Gregory 1997, 193). One person (72 kg) paddling without extra load could travel at 4.4 km/h. While carrying an extra load of 358 kg (for a total of 430 kg), the speed reached was 3.8 km/h. With two persons (151 kg) paddling, the speed increased to 4.7 km/h without extra load, and remained at 3.8 km/h when transporting an extra load of 279 kg. When two persons punted the boat without extra load, the speed reached was only 3.3 km/h. Gregory (1997, 195) notes that sailing is the most efficient technique in terms of energy input and believes that it could surpass paddling in terms of speed under favourable wind conditions, but due to the lack of wind during the experiments this was not tested. Rowing could not be tested as the hull width of the "Daire" dugout was too small. Generally speaking, the speed of boats increases with the length, although modern formulas commonly used in naval architecture are very difficult to apply to a 'standard' dugout due to the difference and large variation in shape, material and surface finishing (Gregory 1997, 247).

These values need to be adapted to accommodate for the environment of the Dutch river area, as here the direction of travel impacts the speed, in contrast to the current-free lake environment where the "Daire" experiments were carried out. For these calculations an average flow of the river of 0.9 m/s will be assumed (Hesselink *et al.* 2007). Taking the speed of 4.4 km/h (1.22 m/s) established by Gregory (1997, 193) as regular travel, this translates to 7.6 km/h (2.12 m/s) in the downstream direction and only 1.2 km/h (0.32 m/s) in the upstream direction. When transporting a load the speed decreases to 7.0 km/h (1.96 m/s) in the downstream direction and 0.6 km/h (0.16 m/s) in the upstream direction.

4.3.4 General conclusions on transport modes

The military population and the local population of the Rhine-Meuse delta had a multitude of transport modes available to them, each with their own specific characteristics. By no means are these modes of transport are always competitive: they may and most likely will have functioned as part of a complementary system (Laurence 1998, 143); for example, transport of goods may have occurred on foot to one site, the by boat to another. This can be a complicating matter in further studies, which will be further elaborated in sections 5.2.4 and 5.3.2. In the previous sections a review has been provided of the available literature data on the characteristics of various modes of transportation, and this section will provide a summary of the data that can be used for further modelling and analysis of transport in the Dutch part of the Roman *limes*. The modelling of transport has to take into account the particularities of the Rhine-Meuse delta. This area consists of various channels that cut through the landscape and as a result form barriers or conduits for movement. This has great consequences for transport possibilities.

Concerning land-based transport, in particular local transport in the Dutch *limes* area, the most common method of transport would have been foot-based travel. The regular pace of a traveller can be considered to be 5 km/h for around 6 hours, or 30 km/day. When porting is involved, through which goods up to about 30 kg can be transported, the range will decrease down to an average of 20 km/day. However, valuable physiological research has been done on foot transport, and these more quantitative approaches that can also include terrain factors are much more suitable for use in modelling transport in the past. The details of these methods will be discussed in sections 5.3.1-5.3.2.

Animal-based transport is also available in the Dutch part of the Roman *limes*. This will primarily have involved oxen, as horses seem to not have been used as pack animals and certainly not as draught animals often, and mules must be imported from outside the region. Horses can transport approximately 90 kg, including a rider, pack and harness, and travel at a speed of roughly 5.6 km/h for 6 to 8 hours. Pack mules can similarly carry approximately 90 kg including pack and harness and travel at a speed of roughly 5.6 km/h. However, mostly they will have moved at lower speeds of 4.8 km/h, since their speed is governed by the driver who will usually travel on foot alongside the mules. Mules were also employed as draught animals, and a pair of mules could probably pull a two-wheeled cart with a load of 500 kg across most compacted terrains (e.g. frequently traversed levees) at a speed of 4 km/h, up to 30 km/day. Across terrains that are less solid (e.g. floodplains, peatlands) this will have been impossible, and the mules will either move at a slower pace to generate more draught power, or will not be able to move the cart at all. Oxen as pack animals can transport approximately 90 kg, but occasionally more depending on their size, at a pace of 3.5 km/h. Across compacted terrains, a pair of oxen would have been able to pull a two-wheeled cart with a load of 550 kg or a four-wheeled wagon with a load of 650 kg at an average pace of 3 km/h for 5 hours, giving them a total range of 15 km/day. Goe and McDowell (1980) and Raepsaet (2002) provide information related to the tractive force that can be generated by mules and oxen, which can be used to model ox- and mule-cart transport. The details will be discussed in section 5.3.3.

Four different watercrafts have been treated in the above review of water-based transport, namely prams, punters, galleys and dugouts. Galleys will have had a primary function as a military craft and will probably only rarely be involved in the transport of goods. Regarding punters, only one has been found in the Dutch river area so not much is known about this type of water-based transport. Prams are the most iconic type of water-based transport in the Dutch part of the Roman *limes*, measuring between 20 and 30 m in length and 3 and 4 m in width. The calculated load capacities for prams found in the Dutch river area varied, from 11,000 and 14,000 kg to 52,000 kg, depending on their size and construction. The original hypothesis was that prams were mostly used for the transport of heavy construction materials, and while this will certainly have played a role, the former two ships are thought to have been primarily used for the transport of less heavy goods such as merchandise (e.g. pottery), hay and straw. Prams could move in a downstream direction at a speed of 8.3 km/h (60-90 km/day), and in the upstream direction at 1.8 km/h (15-20 km/day). They will primarily have been employed in the long-distance transport of goods along the major rivers such as the Rhine and Meuse, largely serving the demands of the Roman military population both inside and outside the Dutch river area (Blom and Vos 2008, 418; Brouwers *et al.* 2013, 20).

In contrast, dugouts can be seen as the representative of water-based transport on more local scales. They are the continuation of local traditions of sailing and were continuously in use even during the presence of the larger prams. Most Roman Period dugouts found in the Dutch river area are between 6-7 m in length, with exceptions up to 12 m. Based on dugouts from the British Isles the maximum load capacity can be estimated to be 1,000-1,200 kg for the average boat, up to 4,500 kg for the largest one, including passengers and transported goods. Experimental data suggest the average dugout to have a downstream speed of 7.0-7.6 km/h and an upstream speed of 0.6-1.2 km/h. This may be greater for longer dugouts, but how much greater exactly is difficult to establish.

4.4 Conclusion

With the information presented above it has become clear that the level of understanding of transport in the Roman Period is quite good in terms of transport that is happening at supraregional scales, due to the availability of both archaeological information and written sources, as well as a long tradition of research. However, much less is known about transport on the local and regional scales, such as the interaction between the local population and the military population in the Dutch part of the Roman *limes*. For a large part this is due to the fact that transport on these scales is not mentioned in the written sources and leaves very few archaeological traces. This circles back to the aims of this study posited earlier: by identifying and quantifying the factors that govern movement and by reconstructing and analysing networks of transport in the Dutch *limes* zone through computational approaches, new avenues can be explored that provide new insights into archaeological questions that remain uncertain or unanswered in traditional research. Leaning on the information presented in this chapter, Chapter 5 will focus on modelling local transport connections using least-cost path approaches. Chapter 6 will then move on to the reconstruction and analysis of networks of transport, in the context of both methodological problems (e.g. how do we reconstruct transport networks from the available datasets?) as well as archaeological problems and questions, related to aspects such as the movement of surplus production and the provisioning of the military population in the Dutch part of the Roman *limes*.

5 Modelling transport connections

5.1 Introduction

Since the interest of the current study is mainly in transport on the local scale in the Dutch part of the Roman Lower Rhine *limes* (as part of the complex of scales on which transport would have occurred), we have only very few archaeological remains to work with due to the immaterial nature of local transport movements. Despite the preservation potential for infrastructural finds such as bridges (e.g. Roymans 2007; Roymans and Sprengers 2012), most archaeological evidence for road constructions pertains the Roman military road that closely followed the course of the Rhine and connected the Roman *castella*. Even in one of the most intensively researched areas, the Kromme Rijn region, the archaeological reconstruction of secondary transport routes had to be mostly based on assumptions and interpolations (Vos 2009, 45). The lack of evidence for such a common activity as movement through a landscape is not a new problem in archaeology, and computational approaches have been used for some time to study movement and patterns of movement instead. In particular, least-cost path analysis has been applied to both predict transport routes and to better understand the reasoning behind routes that are known (Conolly and Lake 2006, 252). The focus of this chapter will be on the various aspects of modelling transport in the Dutch part of the Roman *limes* through least-cost path analysis.

5.2 Methodology for modelling transport routes

Sections 1.4.6.2-1.4.6.4 in the introductory chapter have provided an introduction and background to least-cost path analysis in general and some applications and problems of LCPs in archaeology in particular. This section will focus on modelling potential transport routes. This is not the same as reconstructing routes: reconstruction implies that the route must have existed at one point in time, while the modelling procedure in principle only constructs a route between two given points using a certain methodology chosen by the modeller, regardless of whether or not such a route has actually existed. Constructing potential networks of transport in the Dutch part of the Roman *limes* using the modelled routes is the focus of Chapter 6.

The current section will present the methodologies followed during the application of least-cost path modelling for the construction of transport routes, firstly by expanding on the calculation of costs of the most common and best studied mode of transportation: walking. Establishing the costs of other modes of transport is treated in later sections, and the methodology of iterative modelling of LCPs that was carried out in this study is presented in the final section.

5.2.1 Calculating the costs of walking

The most important decision that has to be made when modelling LCPs for walking is the establishment of the costs that will be taken into account during the analysis. In most archaeological applications a decision is made between energy- and time-based models, and often the reasoning behind choosing either remains implicit. This study makes use of a time-based approach, for the following reasons: firstly, time is a more tangible concept to people travelling in the past, particularly in an area where the limits of time as a finite resource are regularly met (Joyce in prep.). Time that people spent away from their home settlement is lost for other activities such as agriculture, animal husbandry and wood collection. Secondly, energy expenditure can be seen as an important factor especially for longer journeys as people might not always have access to resources and are dependent on economising the resources they have (Murrieta-Flores 2010, 253). In contrast, most movement of the local population in the Dutch river area that we are interested in likely occurred only over relatively short distances, e.g. for the transport of goods between settlements, markets, storage facilities and *castella*, most of which can be travelled within a day. This makes time a more suitable cost currency, as people could have weighted it against other activities that they could have performed. Thirdly, experimental research has shown that across flat areas where only the properties of the terrain vary, people aim to maintain their natural gait rather than economising energy expenditure (De Gruchy *et al.* 2017). This appears to be different from travel in hilly and mountainous areas, where energy-saving practices have been observed (Murrieta-Flores 2010, 254).

Out of the many functions available to calculate costs of movement, the equation offered by Pandolf *et al.* (1977) stood out from the rest by readily incorporating terrain coefficients and carried loads, which are important factors considering the aim to model connections of transport in the natural landscape of the Dutch river area. The original function (Eq. 5.1) is based on experimental data and calculates the metabolic rate (M in W) using as parameters the subject weight (W in kg), external load (L in kg), a terrain coefficient (η), the speed of walking (V in m/s) and slope (G in %).

$$M = 1.5W + 2.0(W + L)\left(\frac{L}{W}\right)^2 + \eta(W + L)(1.5V^2 + 0.35VG) \tag{5.1}$$

In this study slope is not taken into account, as the Dutch river area is largely flat and the greatest elevation differences, ranging only in the tens of metres, occur around the edges of the research area. The slope factor is omitted by setting the slope parameter (G) to 0 (Eq. 5.2).

$$M = 1.5W + 2.0(W + L)\left(\frac{L}{W}\right)^2 + \eta(W + L)1.5V^2 \tag{5.2}$$

Considering that over flat terrains people aim to maintain their natural gait rather than lowering their energy expenditure (De Gruchy *et al.* 2017), the formula can be rewritten to calculate velocity rather than the metabolic rate, firstly by carrying over the elements that are not in a product with V^2 from the right to the left side of the equation (Eq. 5.3).

$$M - 1.5W - 2.0(W + L)\left(\frac{L}{W}\right)^2 = \eta(W + L)1.5V^2 \tag{5.3}$$

Then by dividing both sides by the elements that are in a product with V^2 (Eq. 5.4).

$$\frac{M - 1.5W - 2.0(W + L)\left(\frac{L}{W}\right)^2}{1.5\eta(W + L)} = V^2 \tag{5.4}$$

And finally taking the square root to arrive at V (Eq. 5.5).

$$V = \sqrt{\frac{M - 1.5W - 2.0(W + L)\left(\frac{L}{W}\right)^2}{1.5\eta(W + L)}} \tag{5.5}$$

V can now be used to represent the time it takes to cross a certain distance of terrain in our LCP analysis. The weight (W) of the person that is moving is set as a fixed parameter at 60 kg. Although this is ultimately an arbitrary number, it is a rough average of the optimal weight range according to calculations of the modern body mass index (Keys *et al.* 1972; 2014). Using estimates of the average height of adults in antiquity, ranging between 1.61 and 1.72 m (Roth 1999, 9), the range of optimal weights according to this method was found to be between 48 and 74 kg.

The carried load (L) is a variable that can change depending on which situation the costs aim to represent. As has been established in section 4.3.1, the carried load will not have exceeded two-thirds of a person's body weight, i.e. not more than 40 kg. This limitation was used as the upper bound for modelling LCPs. Furthermore, LCPs were calculated for a carried load of 0 kg, which is evidently the lower bound, and for a carried load of 20 kg, as a realistic average of what a person would be transporting over longer distances.

The metabolic rate (M) is now no longer a variable, but must be fixed at a constant rate based on the assumption that people aim to retain their natural gait over flat terrains. We therefore calculated the metabolic rate as it would be for our subject of $W = 60$ kg while not carrying any load ($L = 0$ kg), travelling over an ideal surface ($\eta = 1$) at a constant velocity of 1.4 m/s (5.0 km/h; Tobler 1993), which equates to 266 W. This contradicts the value of 340 W that was published earlier in a case study that is part of this research (Groenhuijzen and Verhagen 2015, 30), which was erroneously based on a constant velocity of 6.0 km/h. While the introduction of this error is unfortunate, it does not greatly affect the results and conclusions drawn in that study as the error was applied equally over the modelled cost rasters.

5.2.2 Incorporating the natural environment into walking costs

The implementation of the terrain coefficient (η) warrants its own discussion, as it is the parameter that ties the natural environment of the research area to the calculation of time as cost currency for modelling LCPs of walking. Soule and Goldman (1972) have developed terrain coefficients for a precursor of the formula that was later published by Pandolf *et al.* (1977). These figures were published again later by Brannan (1992). Their terrain coefficients are related to surface type and vegetation, and not directly to landscape types such as those that have been constructed as palaeogeographic units in the palaeogeographic map of the Dutch part of the Roman limes (Chapter 2), which only have an implied associated surface type and hydrology and vegetation, and not explicitly mapped ones. Based on these associated variables, although not ideal, a rough conversion can be made between the palaeogeographic units and terrain types, shown in Table 5.1.

Terrain type/palaeogeographic unit		Coefficient
Terrain type (Soule and Goldman 1972, 708)		
Paved road		1.0
Dirt road		1.1
Light brush		1.2
Heavy brush		1.5
Swampy bog		1.8
Loose sand		2.1
Palaeogeographic unit (this study)		
Natural levees	High natural levees	1.1
	Moderately high natural levees	1.1
	Low natural levees	1.2
	Residual gullies	1.5
Floodplains	High floodplains	1.5
	Low floodplains	1.8
Peatlands	Eutrophic peatlands	1.8
	Mesotrophic peatlands	1.8
	Oligotrophic peatlands	1.8
Dunes and beach ridges		1.5
Tidal flats		20.0
Coversands		1.2
River dunes		1.2
High Pleistocene sands		1.5
Fluvial terraces		1.2
Rivers and streams		20.0

Table 5.1. Terrain coefficients for the terrain types by Soule and Goldman (1972, 708) and the palaeogeographic units used in this study.

The high levees were equated with dirt roads, based on the assumption that most habitation and movement occurred on these levees and thus easily traversable routes will have formed here. The low levees, coversands, river dunes and fluvial terraces were equated with light brush due to a lower frequency of travel but still a relatively dry and largely deforested terrain in the Roman period. The dunes and beach ridges and the high Pleistocene sands were given the value of heavy brush, not only due to an assumed higher amount of vegetation, but also to partly reflect the difficulty of travel across the minor relief differences in these terrains. The high floodplains, as intermediary between levees and the large expanses of floodplains and peatlands, were also given the value of heavy brush. As wet and unattractive parts of the landscape, the low floodplains and peatlands were given the value of a swampy bog. The rivers and streams and tidal flats were given an arbitrary high value of 20, to function as barriers for travel on foot. This may not be entirely realistic, as some form of local infrastructure was likely present and some parts of the local infrastructure across streams (i.e. bridges) are known (e.g. Roymans 2007; Roymans and Sprengers 2012; see also Hiddink and Roymans 2015, 48–50). The function of rivers and streams a barrier changes when water-based transport becomes available, which is discussed in section 5.2.4.

Using the above presented formula to calculate speed with the terrain coefficients of Table 5.1, the time it takes to travel 50 m for various terrains and varying loads is given in Table 5.2. These are the values that can be implemented in cost rasters for the calculation of LCPs of travelling on foot, and this study will apply those for loads of 0, 20 and 40 kg.

Palaeogeographic unit		**Coefficient**	**Time in s over 50 m with L =**				
			0 kg	**10 kg**	**20 kg**	**30 kg**	**40 kg**
Natural levees	High natural levees	1.1	37.5	40.5	43.3	45.9	48.4
	Moderately high natural levees	1.1	37.5	40.5	43.3	45.9	48.4
	Low natural levees	1.2	39.2	42.3	45.2	48.0	50.6
	Residual gullies	1.5	43.8	47.3	50.6	53.6	56.5
Floodplains	High floodplains	1.5	43.8	47.3	50.6	53.6	56.5
	Low floodplains	1.8	48.0	51.8	55.4	58.8	61.9
Peatlands	Eutrophic peatlands	1.8	48.0	51.8	55.4	58.8	61.9
	Mesotrophic peatlands	1.8	48.0	51.8	55.4	58.8	61.9
	Oligotrophic peatlands	1.8	48.0	51.8	55.4	58.8	61.9
Dunes and beach ridges		1.5	43.8	47.3	50.6	53.6	56.5
Tidal flats		20.0	159.9	172.7	184.6	195.8	206.4
Coversands		1.2	39.2	42.3	45.2	48.0	50.6
River dunes		1.2	39.2	42.3	45.2	48.0	50.6
High Pleistocene sands		1.5	43.8	47.3	50.6	53.6	56.5
Fluvial terraces		1.2	39.2	42.3	45.2	48.0	50.6
Rivers and streams		20.0	159.9	172.7	184.6	195.8	206.4

Table 5.2. Time (in s) to travel 50 m across a terrain with a given terrain coefficient, calculated for varying loads L (in kg).

5.2.3 Calculating the costs of mule- and ox-cart transport

Besides travel on foot, a number of other transport modes were potentially available to the local and military population of the Dutch part of the Roman *limes*. Based on the information presented in section 4.3.2, the options that will be covered here are mule-cart and ox-cart transport. Of these, the ox-cart is likely the most common due to the widespread availability of oxen and the material evidence of the use of yokes (Nicolay 2007, 250–56). The use of mules is likely less common, but cannot be entirely ruled out in the Dutch river area. Both mules and oxen can also be used as pack animals, but in these instances the movement of the animals will have been governed by the driver who is likely travelling on foot. For the most part the costs (and the resulting modelled routes) for foot-based transport will suffice, although it must be kept in mind that oxen, in contrast to mules, are generally slower than foot-based transport.

In contrast to the widespread availability of physiological and/or experimental functions for modelling the costs of walking, much less research has been done on modelling time or energy expenditure of animal-based transport modes. A function for calculating the required traction force (T in kgf) to move a pulled load (P in kg) over a surface with a certain friction (k) and slope (i in m/m) is given by Raepsaet (2002, 24; Eq. 5.6).

$$T = k\,P + P\,i \tag{5.6}$$

Verhagen *et al.* (2014, 79–80) in their study of Roman roads in Cappadocia provide the only found implementation of this formula in a computational archaeological approach, in order to calculate maximum slope that can be travelled for a 500 kg mule-cart. Assuming a traction force for a pair of mules of 93 kgf (50 kgf per mule × 1.86 for the efficiency loss of a pair) and a friction coefficient of 0.10, the maximum slope was found to be 9%. For the Dutch river area however, slope is unlikely to have played a role. For movement over horizontal ground, Raepsaet (2002, 23) finds a linear relation between the traction force and pulled load via a friction coefficient (f; Eq. 5.7).

$$T = f\,P \tag{5.7}$$

The friction coefficient is subject to a large variation, primarily based on the nature of the contact surface, but also on the axel friction and on whether or not the cart is already moving. Raepsaet (2002, 22) references 18th and 19th century experiments for the establishment of this coefficient, finding a range between 0.01 and 0.50. For a wood on a wet grass contact surface, f is found to be 0.50 from a static position and 0.35 when moving. For moving wooden wheels on dry grass f equals 0.25 (Raepsaet 2002, 23). For iron-rimmed wheels, movement over fields and light brush provides an f of 0.10-0.15, over marshy land 0.20-0.40, over a rough stone path 0.06, over a muddy beaten path 0.04, over a paved road 0.02, and over a cemented road 0.01 (Raepsaet 2002, 24). In their review on modern traction in non-industrial countries, Goe and McDowell (1980, 6) find values for f ranging between 0.01 for hard surfaces to 0.25 for very wet or sandy ground, although these values only include friction of the contact surface and not axel friction. Goe and McDowell (1980, 7) also provided some values on a wooden-wheeled cart weighing a total of 849 kg, of which the transported load constitutes 597 kg. Such a cart requires a draught of 36 kgf on a dirt road and 127 kgf on a ploughed field. Given Equation 5.7, this suggests values for f of 0.042 and 0.15 respectively.

The amount of traction force that can be produced not only differs per animal, but is also dependent on the speed at which the force is generated. A function for the calculation of tractive horsepower (HP in hp; 1 hp = 735.5 W) is given by Goe and McDowell (1980, 3) including traction force (T in kgf) and speed (V in km/h) as parameters (Eq. 5.8).

$$HP = \frac{T\,V}{270} \tag{5.8}$$

Equation 5.8 can be rewritten to calculate traction force instead (Eq. 5.9).

$$T = \frac{270\,HP}{V} \tag{5.9}$$

The maximum horsepower of mules is approximately 0.9 hp, and of oxen 1.1 hp. However, these are the maximum values for modern animals and likely do not reflect the generally smaller stature of mules and particularly oxen in the Dutch river area in the Roman period. More likely, the horsepower of Roman mules and oxen are both in the range of 0.7 hp, similar to their medium-sized modern equivalents (Goe and McDowell 1980, 38). For a pair of animals, this would be equal to 0.7 × 1.86 = 1.3 hp. Given these values, the maximum generated traction force of animals can be calculated for various speeds, shown in Table 5.3 and Figure 5.1.

***V* (km/h)**		0.5	1	1.5	2	2.5	3	3.5	4
***T* (kgf)**	**1 animal**	378	189	126	95	76	63	54	47
***T* (kgf)**	**2 animals**	703	352	234	176	141	117	100	88

Table 5.3. Maximum generated traction force for various speeds, based on 0.7 and 1.3 hp.

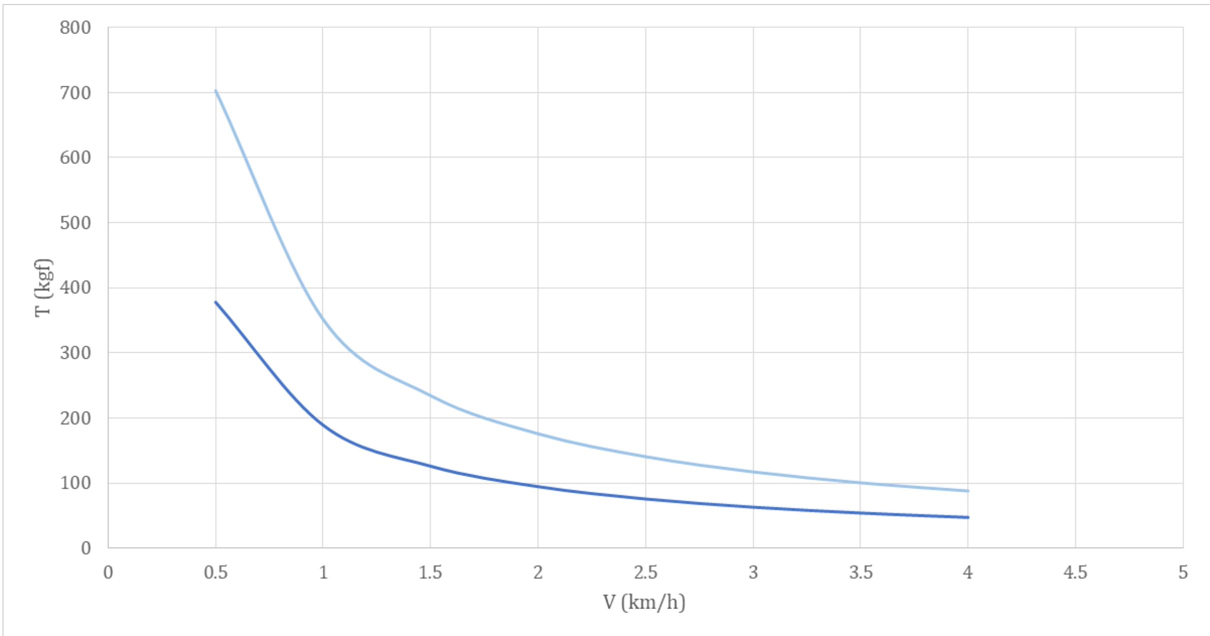


Figure 5.1. Maximum generated traction force (T) versus speed (V) for one (dark blue) or two (light blue) draught animal(s).

One important thing to note here is that it thus does not seem impossible to move a cart even across difficult terrains, it will just move at relatively low speeds. Carts may also get stuck in particularly wet or unconsolidated terrains, but this is more difficult to implement and is thus not explicitly taken into account.

Rather than calculating the required traction force, the above mentioned formulas can also be combined to calculate speed (V in km/h) based on the available horsepower (HP in hp), pulled load (P in kg) and a friction coefficient (f; Eq. 5.10), which will be more in line with the calculations for travelling on foot that are used in the calculation of LCPs in this study.

$$V = \frac{270\ HP}{f\ P} \quad (5.10)$$

The assumption that has to be made here is that the horsepower generated is always at a constant level (set here at 0.7 hp for one draught animal and 1.3 for a pair of draught animals), which is not necessarily true. Typical loads of two-wheeled carts in the Roman period were found to be 500 kg for mules and 550 kg for oxen (see section 4.3.4). Using the earlier mentioned wooden-wheeled cart of Goe and McDowell (1980, 7), this amounts to a total weight of 752 and 802 kg respectively. The function now calculates speed for mule- and ox-carts (bounded to the animals' maximum speed of 4 and 3.5 km/h respectively) that is only dependent on the friction coefficient, which in turn is mostly dependent on the nature of the contact surface, i.e. the natural terrain (Fig. 5.2).

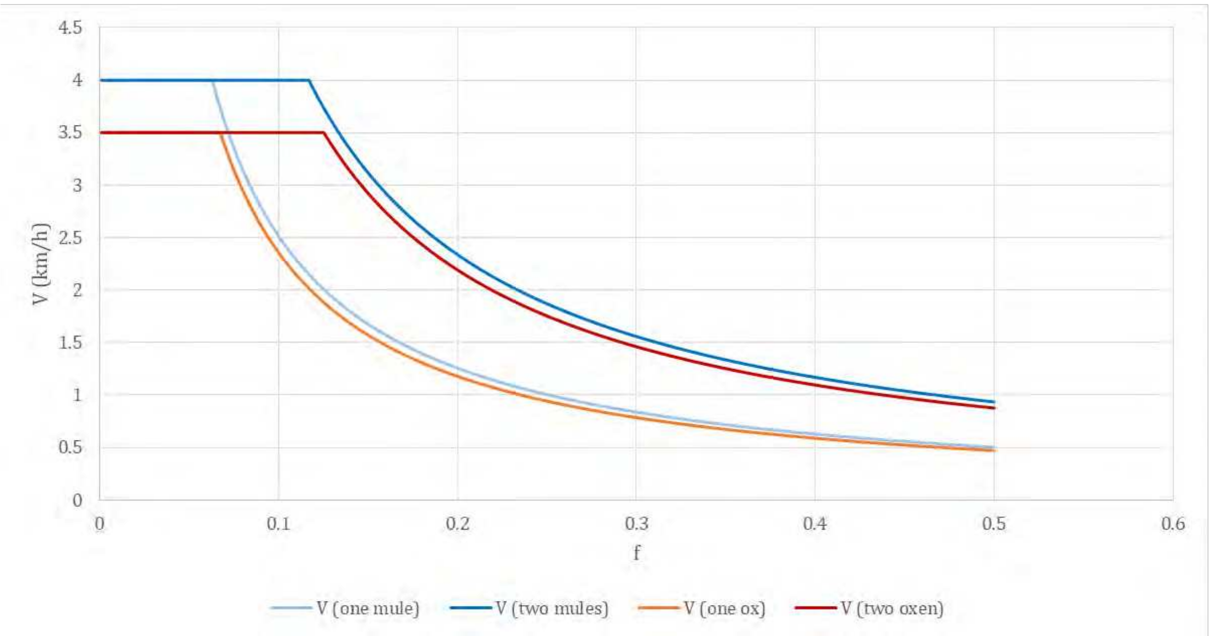


Figure 5.2. Speed (V) versus the friction coefficient (f) for mule- and ox-carts drawn by one or two animals.

In order to use this information to calculate the costs (in terms of time) of travelling through the terrain of the Dutch river area, the only difficulty that remains is to connect the friction coefficients to the palaeogeographic information. In contrast to travel on foot, the data available on friction coefficients across different terrains for carts are much less precise and more difficult to connect to the terrains of the palaeogeographic map. The values for friction coefficients applied in this study and the resulting time it takes to travel 50 m for mule-carts (carrying 500 kg) and ox-carts (carrying 550 kg) pulled by a single animal or a pair of animals is presented in Table 5.4.

For travel on foot, high levees were equated to dirt roads, based on the assumption that more easily traversable routes would have been present on these levees as the result of the concentration of habitation and movement. However, it is likely that not all of these routes are of equal traversability for carts. Therefore, a friction coefficient of 0.10 was chosen as an intermediate between a dirt road and a ploughed field (to represent a less compacted terrain, following Goe and McDowell 1980, 7). The low levees, coversands, river dunes and fluvial terraces in turn were given the full coefficient of ploughed fields of 0.15. The low floodplains and peatlands were placed at the highest end of the spectrum with a coefficient of 0.50, to classify them as the wettest and least attractive parts of the landscape to move a cart through. The dunes and beach ridges, high Pleistocene sands and high floodplains were simply put at roughly one-third between these values, at 0.25. The rivers and streams and tidal flats were again given an arbitrary high value of 2, to function as barriers for movement (similar in magnitude to the arbitrarily high terrain coefficient of 20 for movement on foot; see also Table 5.2). Of course this would not always be the case, as bridges and fords were known to be present, but because so little is known on these parts of the local infrastructure, they could not be included in the analyses performed in this study. The resulting times over a distance of 50 m of a certain terrain can be implemented in cost rasters to model LCPs of cart-based transport, and this study will only apply those for mule-carts and ox-carts pulled by a pair of animals.

Palaeogeographic unit		Coefficient	Time in s over 50 m for:			
			Mule (single)	Mule (pair)	Ox (single)	Ox (pair)
Natural levees	High natural levees	0.10	71.6	45.0	76.4	51.4
	Moderately high natural levees	0.10	71.6	45.0	76.4	51.4
	Low natural levees	0.15	107.4	57.8	114.6	61.6
	Residual gullies	0.25	179.0	96.3	191.0	102.7
Floodplains	High floodplains	0.25	179.0	96.3	191.0	102.7
	Low floodplains	0.50	358.1	192.5	381.9	205.3
Peatlands	Eutrophic peatlands	0.50	358.1	192.5	381.9	205.3
	Mesotrophic peatlands	0.50	358.1	192.5	381.9	205.3
	Oligotrophic peatlands	0.50	358.1	192.5	381.9	205.3
Dunes and beach ridges		0.25	179.0	96.3	191.0	102.7
Tidal flats		2.00	1432.4	770.1	1527.6	821.3
Coversands		0.15	107.4	57.8	114.6	61.6
River dunes		0.15	107.4	57.8	114.6	61.6
High Pleistocene sands		0.25	179.0	96.3	191.0	102.7
Fluvial terraces		0.15	107.4	57.8	114.6	61.6
Rivers and streams		2.00	1432.4	770.1	1527.6	821.3

Table 5.4. Time (in s) to travel 50 m across a terrain with a given terrain coefficient, calculated for mule- and ox-carts pulled by a single animal or a pair of animals.

5.2.4 Water-based transport as part of multimodal transportation

Besides land-based transport modes, the local and military population of the Dutch part of the Roman Lower Rhine *limes* have also used water-based transport options, as attested by a number of archaeological finds including both dugouts and larger river ships such as prams. The movement of goods over water must most often be envisioned as part of a multimodal transport network, as it is only a rare occurrence that both the source and the destination of the goods are on the water. Of all available watercrafts, the dugout is probably the best representative of local transport, as the larger transport ships are primarily used for the transport of goods on interregional to imperial scales. For this reason, only the dugout will be included as an option for multimodal transport networks.

Wheatley and Gillings (2002, 156–57) have modelled water-based movement as part of multimodal paths in a manner that can be related to the case of the Dutch river area in the Roman period. They represent waterways as low-cost corridors of movement that are accessible after overcoming a small barrier of high cost that represents the transfer between modes. Their line of thought will be followed in this study. Furthermore, water-based movement differs from land-based movement in the Dutch river area in that it is directional: upstream movement is more difficult than downstream movement. The method through which these factors are accounted for will be explained in the following paragraphs.

In general, the calculation of a LCP of a multimodal transport connection follows the same methodology as that of unimodal land-based transport connections. The most important part is thus the establishment of the costs of travel in a cost raster. As long as the transport is land-based, this is simply equal to the costs that were calculated earlier for travel on foot, mule-cart or ox-cart transport, which have been presented above. The only difference has to be made in the costs of movement over the palaeogeographic unit of 'rivers and streams', which should now accommodate water-based movement rather than form a barrier of artificially high costs. In section 4.3.3.2 the speed of an average-sized dugout with load was established at 7.0 km/h (2.12 m/s) in the downstream direction and 0.6 km/h (0.16 m/s) in the upstream direction. Over the course of 50 m, the upstream travel time would be 312.5 s, which can be implemented in the cost raster as the standard cost value for water-based transport over the unit of 'rivers and streams'.

To accommodate for the directional aspect, specifically the faster downstream movement, a vertical raster is included besides the regular cost raster, to be able to calculate the accumulated cost surface through the Path Distance procedure in ArcGIS. Within this vertical raster, the cells that are part of the 'rivers and streams' palaeogeographic unit are given artificial elevation values that model a slope between 0° and 1° in the downstream direction (Fig. 5.3).

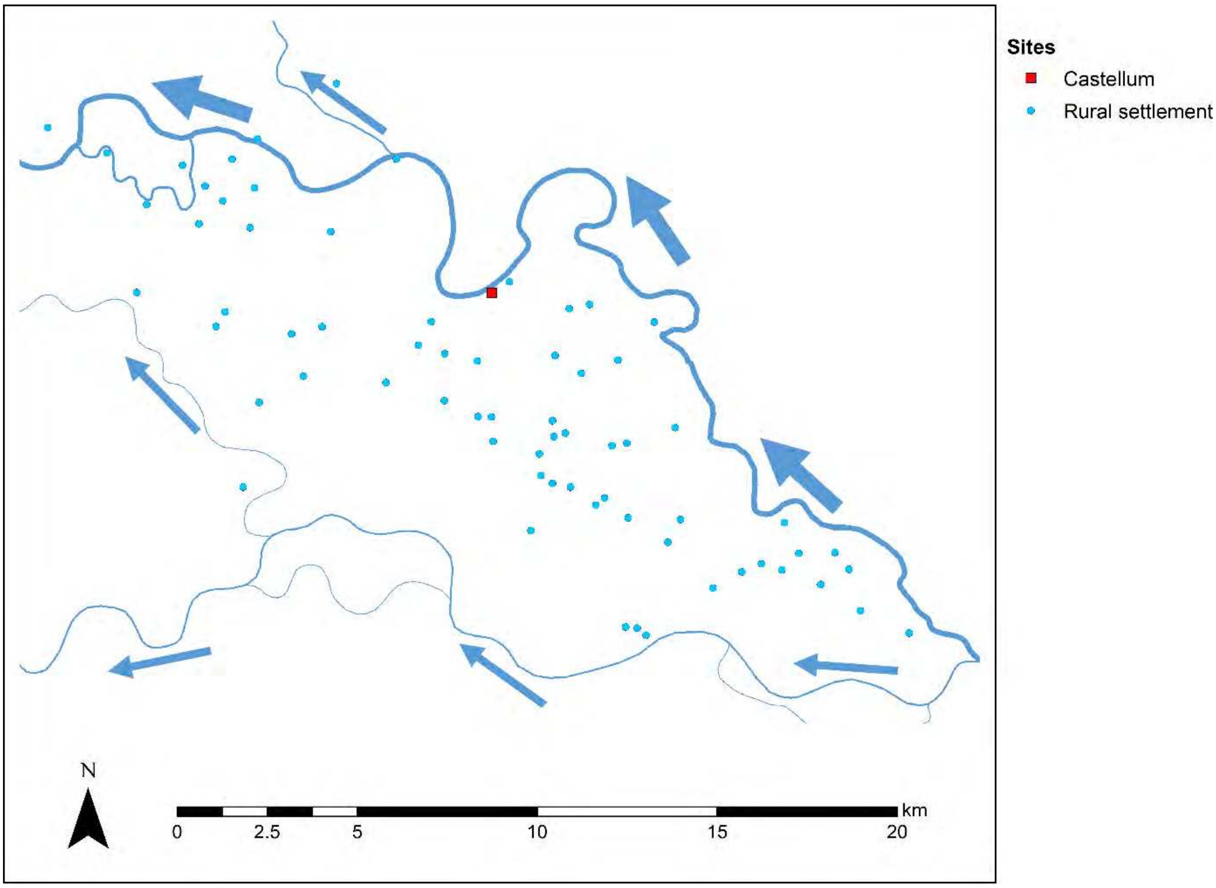


Figure 5.3. The flow direction of rivers in the Kromme Rijn region, a part of the research area, with settlements shown for that have been dated to the Early Roman Period A. Following the methodology described, the highest artificial elevations would be in the southeast corner, and the lowest in the northwest and southwest corners, to model a downslope in the downstream direction.

Furthermore, to include the access costs of water-based transport (i.e. the transfer between a land-based mode and a water-based one), all palaeogeographic 'land' units are given an artificial elevation value that is about a hundred times larger than those of the 'rivers and streams' unit. The effect of this is that the slope when moving from 'land' cells to 'water' cells and vice versa approaches 90° and -90° respectively. The conversion table to vertical factors that is then used in this study is shown in Table 5.5.

Using the values from Table 5.5 for calculating the accumulated cost surface in the Path Distance procedure, travel in the upstream direction (represented by a slope between 0.0001° and 1°) remains unmodified from the standard value of 312.5 s through the application of a vertical factor of 1. In contrast, travel in the downstream direction (represented by a slope between -1° and 0°) is now modified by a vertical factor of 0.075, resulting in a travel time over 50 m of 23.4 s. This is a good approximation of the actual time it would take assuming a downstream speed of 7.0 km/h (23.6 s), only differing as the result of the rounding that occurs when applying the vertical factor. Finally, an additional access cost X can be assigned to movement from 'land' units to 'water' units and vice versa (represented by slopes smaller than -1° and greater than 1°), which in this study is set at 2 (resulting in a vertical factor of 3), although this is ultimately a subjective decision.

Slope (°)	Vertical factor
≥ -90	1 + *X*
≥ -1	0.075
≥ 0.0001	1
≥ 1	1 + *X*
90	1 + *X*

Table 5.5. The conversion table from slope (derived from the vertical raster) to a vertical factor, wherein X denotes additional access costs.

5.2.5 Iterative modelling of least-cost paths

It is a fairly easy process to model a single LCP using commonly available tools in a GIS environment, such as the Cost Distance or Path Distance procedures in combination with the Cost Path procedure in ArcGIS, which have been discussed in section 1.4.6.4. However, in this study one of the aims is to model networks of transport, and that requires the need for a large number of LCPs to represent transport connections between a large number of places. This section will present the methodology that was followed to iteratively calculate LCPs between all sites in the archaeological site dataset (Chapter 3) that is used in this study.

Besides the ArcMap interface that provides access to the LCP tools in ArcGIS, the software also provides a scripting package under the name ArcPy, which can be used to apply spatial procedures of ArcGIS in the Python programming language. Python scripts (Appendix 2) were written to automatically and iteratively calculate LCPs between all archaeological sites according to the workflow presented in Figure 5.4. As input this model utilises the archaeological site dataset, one of the modelled cost rasters (e.g. foot travel or ox-cart transport), and optionally a vertical raster and vertical factor conversion table when including water-based transport, to account for the directionality of this mode (see section 5.2.4). One of the sites is then selected as the source site for LCP calculations, and the accumulated cost surface and cost backlink are calculated. If water-based transport is included, this makes use of ArcGIS's Path Distance procedure, otherwise it utilises the Cost Distance one. It then iterates through all other sites to calculate the LCPs between those destinations and the source, which form the output of the model. Once the loop through the destination sites is finished, the model returns to the start to select a new source site, and continues doing so until all sources are processed. When not including water-based transport, the number of destinations can be halved due to the lack of directionality (i.e. the path from site B to site A does not have to be calculated when the path from site A to site B is already known).

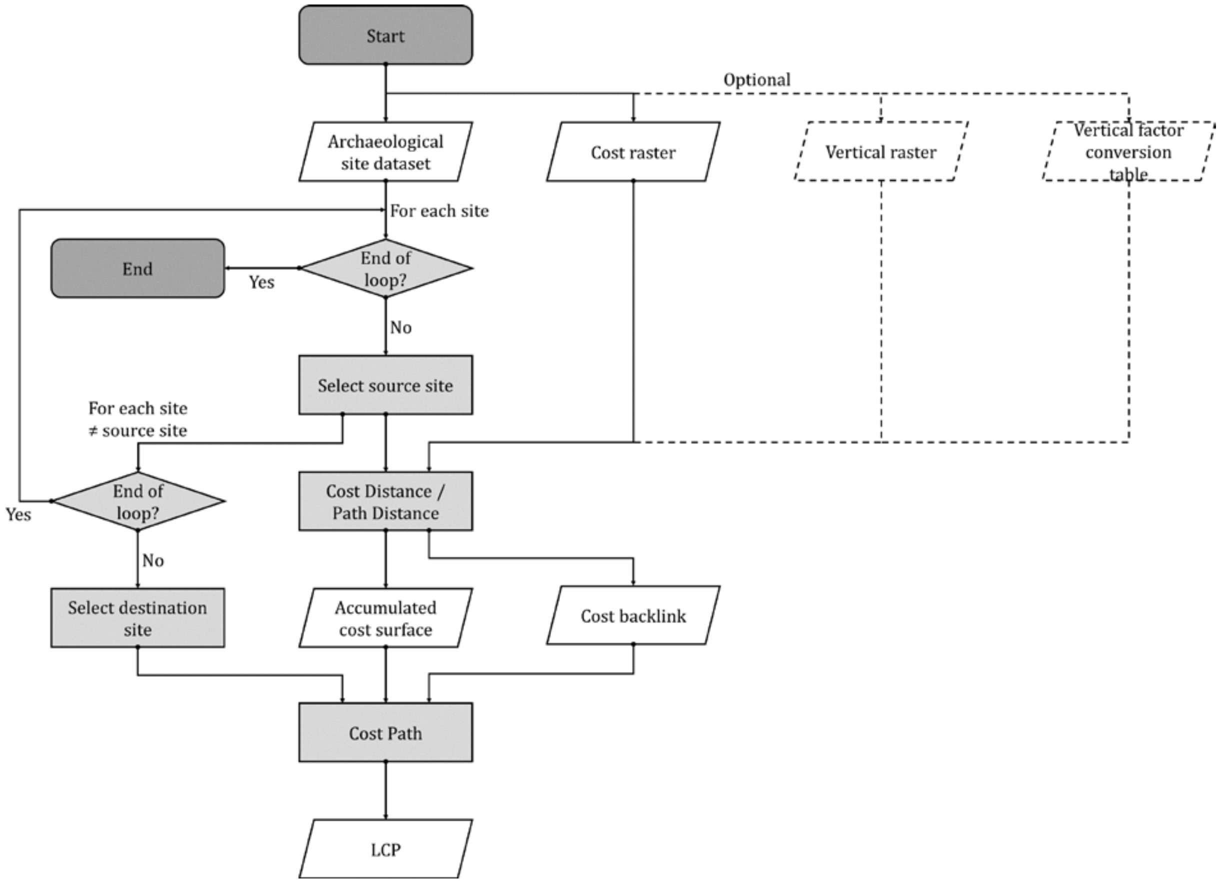


Figure 5.4. Flowchart of the procedures followed to iteratively model LCPs between all sites in the archaeological site dataset.

A final optional step, not included in the workflow in Figure 5.4, is to extract data on the LCP immediately. The data that is relevant to know for modelling networks of potential transport connections are the source, destination, length and cost (i.e. travel time) of the LCP. The exact route is not important when constructing transport networks, and thus LCPs that are only used for this purpose do not necessarily need to be saved after the required data is extracted, saving both storage space and processing time.

5.3 Results: a case study of the Kromme Rijn region

Following the processes outlined above, LCPs were modelled within this study for various purposes and for various research windows, ranging from local case studies to the entire research area, the Dutch part of the Roman *limes*. Their primary application has been in the study of networks of transport, which will be the focus of Chapter 6. The exact route that the LCP follows in the landscape is not relevant for the study of networks through network analysis, as the characteristics of that route, i.e. the length and particularly the travel time of the route, are more important. Therefore, the rasters that contain the LCPs themselves were not saved for the entire research area (i.e. the Dutch part of the Roman *limes*), saving time and hard drive space. This section will thus present and examine the results of the modelling of transport connections only for a single case study, namely that of the Kromme Rijn region in the central part of the Dutch river area (Fig. 5.5).

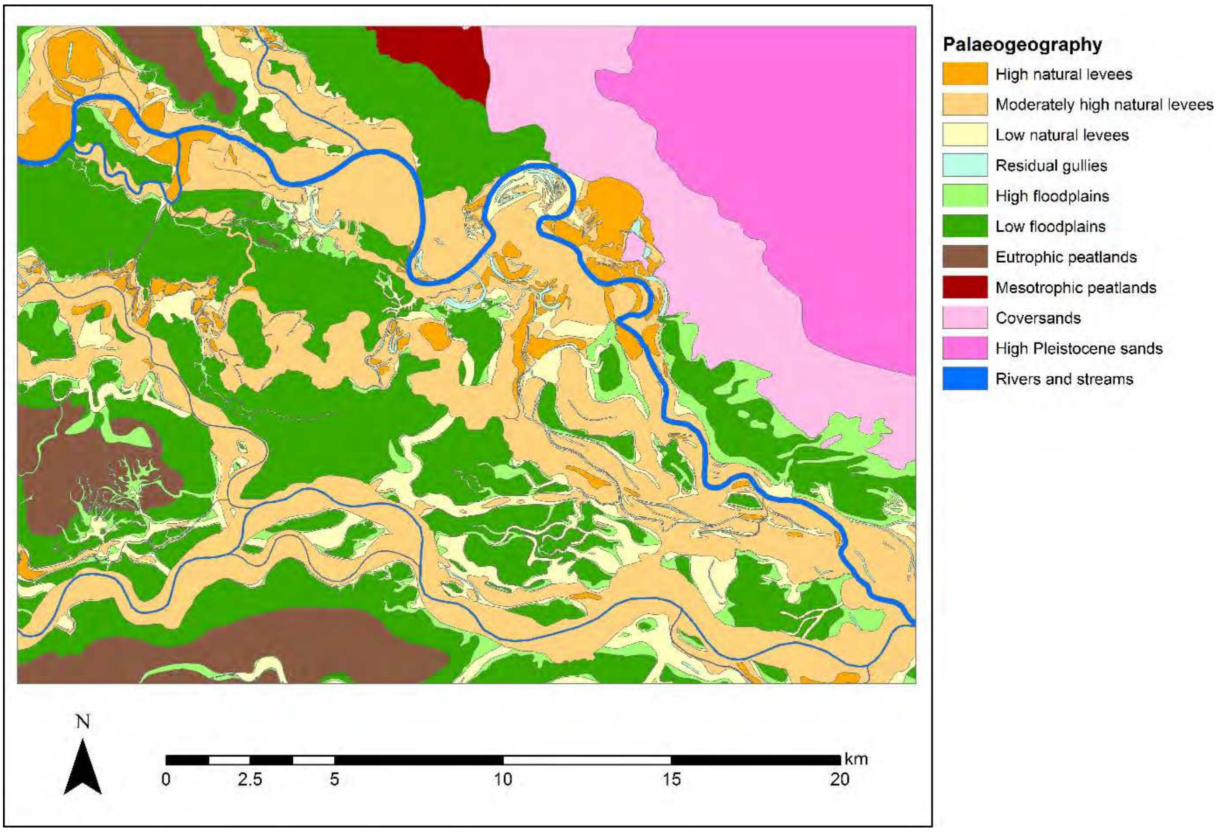


Figure 5.5. Overview of the Kromme Rijn region.

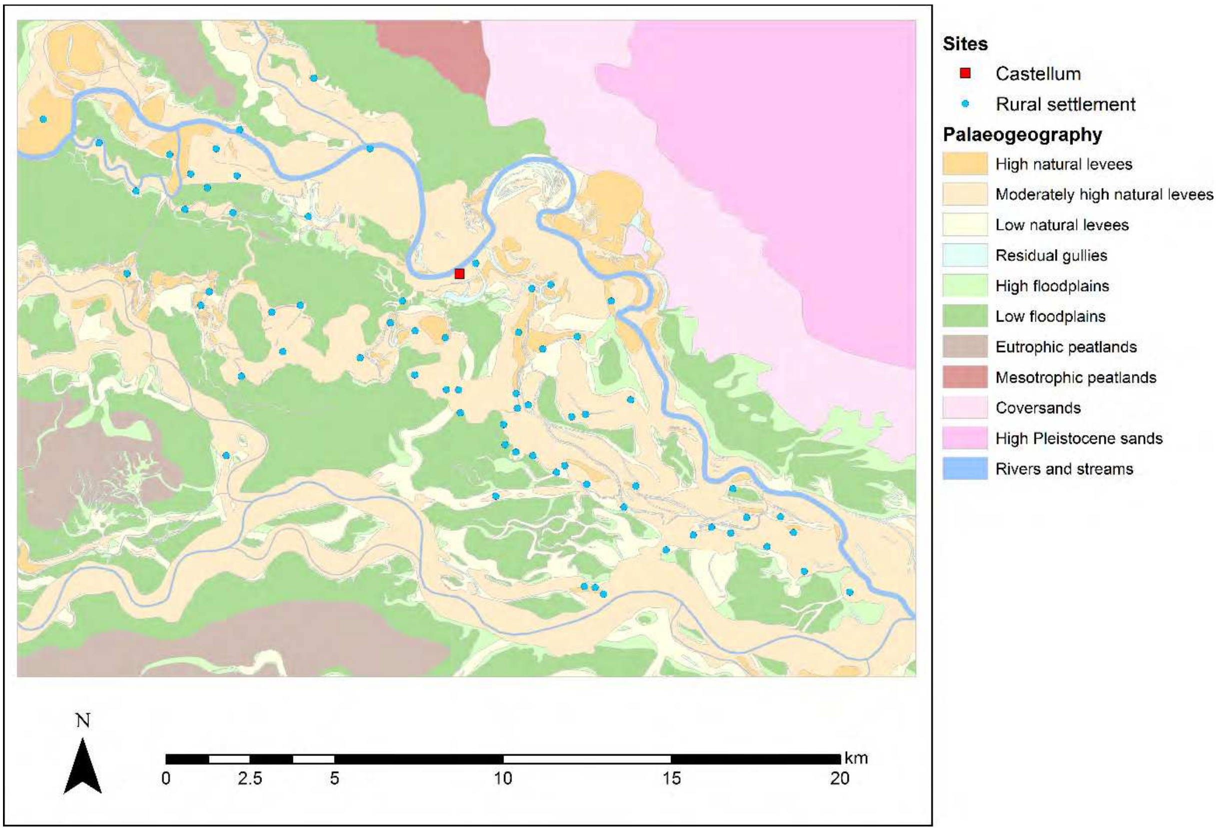


Figure 5.6. Overview of the rural settlements and the castellum *present during the Early Roman Period A in the Kromme Rijn region.*

The reason why the LCPs were saved for the Kromme Rijn region and not for other areas is because it was the subject of preliminary research in this project on modelling different transport modes, which was presented at the Landscape Archaeology Conference (LAC) in Rome in 2014 (Groenhuijzen and Verhagen 2015) and at the Computer Applications and Quantitative Methods in Archaeology (CAA) conference in Siena in 2015 (research included in sections 5.2.4 and 5.3.2). The Kromme Rijn region was chosen as a case study area for these preliminary studies because it is well-researched both in terms of palaeogeography (e.g. Cohen *et al.* 2012) and archaeology (e.g. Vos 2009). Besides the geographic delimitations, in order to maintain focus on the modelling of transport connections the case study presented here will also apply a limited chronological window. This study will therefore only include settlements and military sites that have a 50% or greater probability of having 10 or more finds in the Early Roman Period A, per the reinterpretation of the chronological information presented in Chapter 3 (based on Verhagen *et al.* 2016b). This results in a dataset of 69 sites, of which 68 are rural settlements and one is a *castellum* (Vechten) (Fig. 5.6).

5.3.1 Modelling land-based transport connections

The construction of the cost rasters for the Kromme Rijn region followed the procedures detailed in section 5.2. This region has a diverse landscape, with broad levees that are most suitable for habitation and transport, smaller floodplains in between, and some peatlands and sandy areas along the margins of the case study area. The resulting cost raster for foot travel without carrying a load is shown in Figure 5.7.

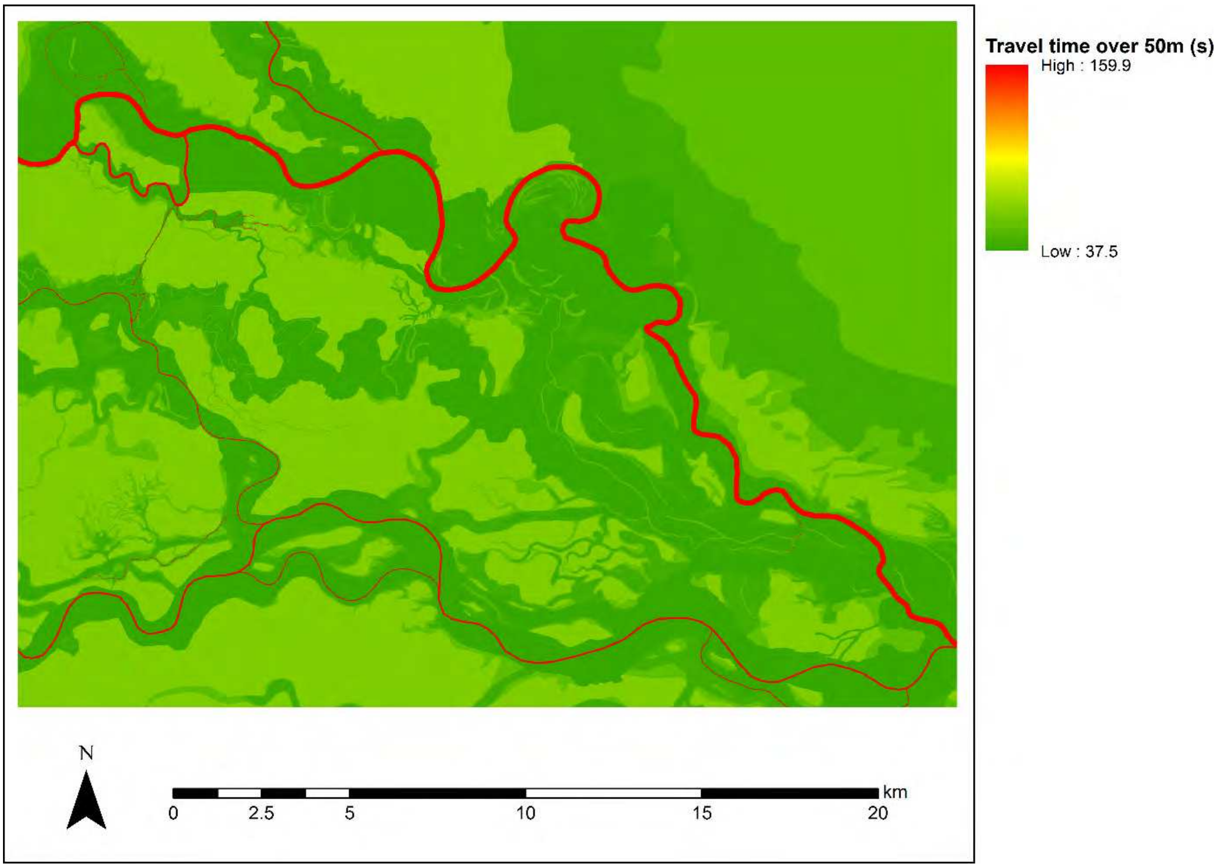


Figure 5.7. Cost raster of the Kromme Rijn region for local foot travel without carrying a load.

When modelling LCPs on this cost raster, paths tend to run in parallel courses and make sharp turns rather than concentrate in smoothed narrow bands, due to the presence of large areas of equal cost (Fig. 5.8). This characteristic was also seen in a study on LCPs in predictive modelling in the eastern Netherlands, and was there manipulated by multiplying the cost raster with a raster of random noise, so that paths converge in corridors of movement rather than run long parallel courses (Verhagen 2013, 386). This method was applied here as well, by introducing a random noise raster with values between 0.9 and 1.1 and multiplying that with the cost raster. The modelled transport connections for regular foot travel based on this new cost raster are shown in Figure 5.9.

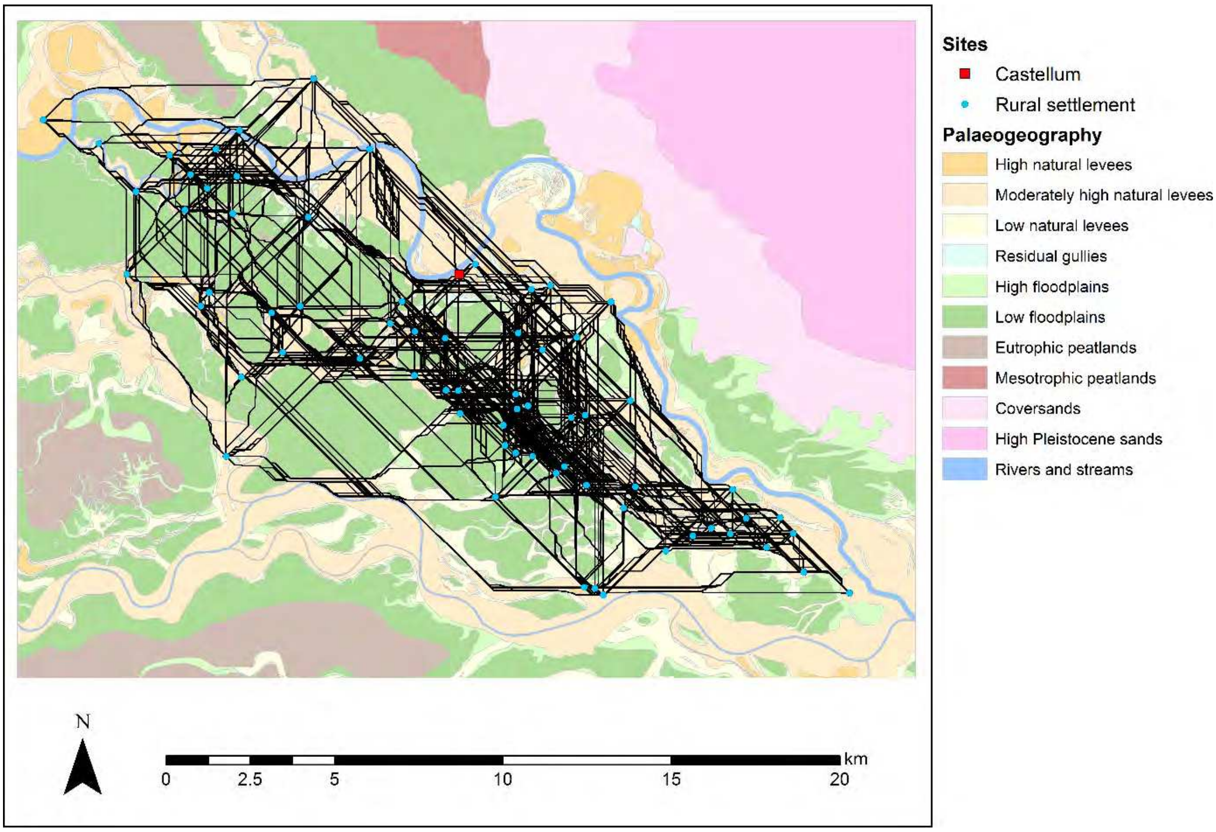


Figure 5.8. Modelled transport connections for local foot travel without carrying a load on the unmodified cost raster.

Most movement occurs on the moderately high natural levee that is centrally located in this case study area. This was also to be expected, as a majority of settlements are also located on these levees. Nonetheless, many transport connections still run across the floodplains, indicating that for regular foot travel in these cases the reduction in speed is not great enough to make a detour a time-saving alternative. The rivers, and particularly the Rhine that flows from the southeast to the northwest, act as barriers for movement on foot. Most paths that have to cross a river only do so once, with the exception of the paths that cross the largest meander bend just north of the only *castellum* in the Early Roman Period A this case study. It appears that the size of this meander bend makes a detour less attractive than crossing the river twice. Of course this is an artificial product of the arbitrary barrier costs assigned to the river: if the costs were set higher, the detour would become increasingly more attractive.

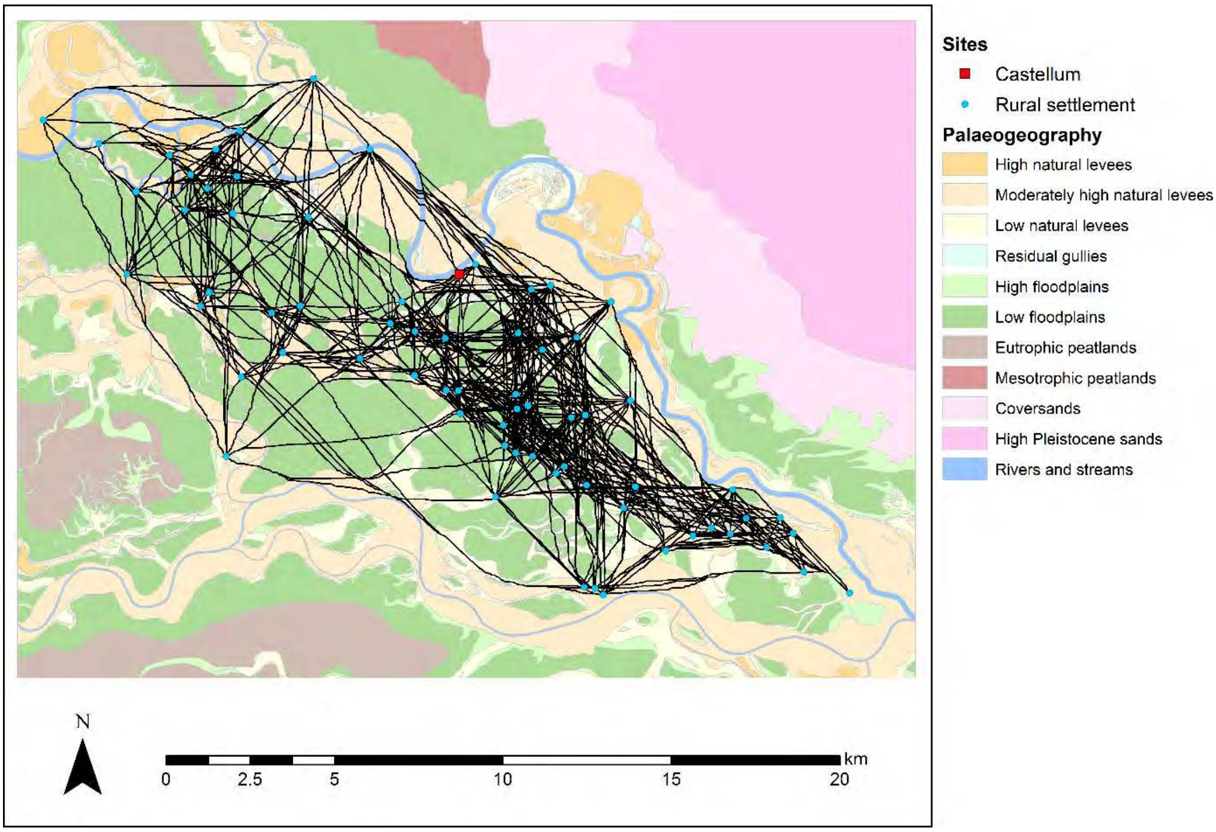


Figure 5.9. Modelled transport connections for local foot travel without carrying a load on the cost raster including random noise.

The resulting routes from LCP modelling of foot travel while carrying loads of 20 and 40 kg (Fig. 5.10) do not differ significantly from those of foot travel without load. This may be attributed to the fact that speed generally decreases when carrying heavier loads, but the decrease in speed is spread relatively equally over the various terrains in the landscape. The real effect thus remains to be seen in the construction of networks out of these modelled transport connections in Chapter 6, wherein the actual travel time of a route is important.

There is a marked difference between the modelled routes of foot travel and those of animal-based transport. Mule-cart and ox-cart (Fig. 5.11) transport routes were modelled following the principles outlined in section 5.2.3. The resulting routes are almost exclusively located on the natural levees and occasionally the high parts of the floodplains, and only very incidentally cross the low floodplains when a detour is disproportionally longer. There is not much difference between the routes of mule-cart and ox-cart transport, which was expected since both were modelled following the same methodology. However, there is a difference in travel time on a route, and thus the main effects of the different modes remain to be seen during the construction of networks of transport in Chapter 6.

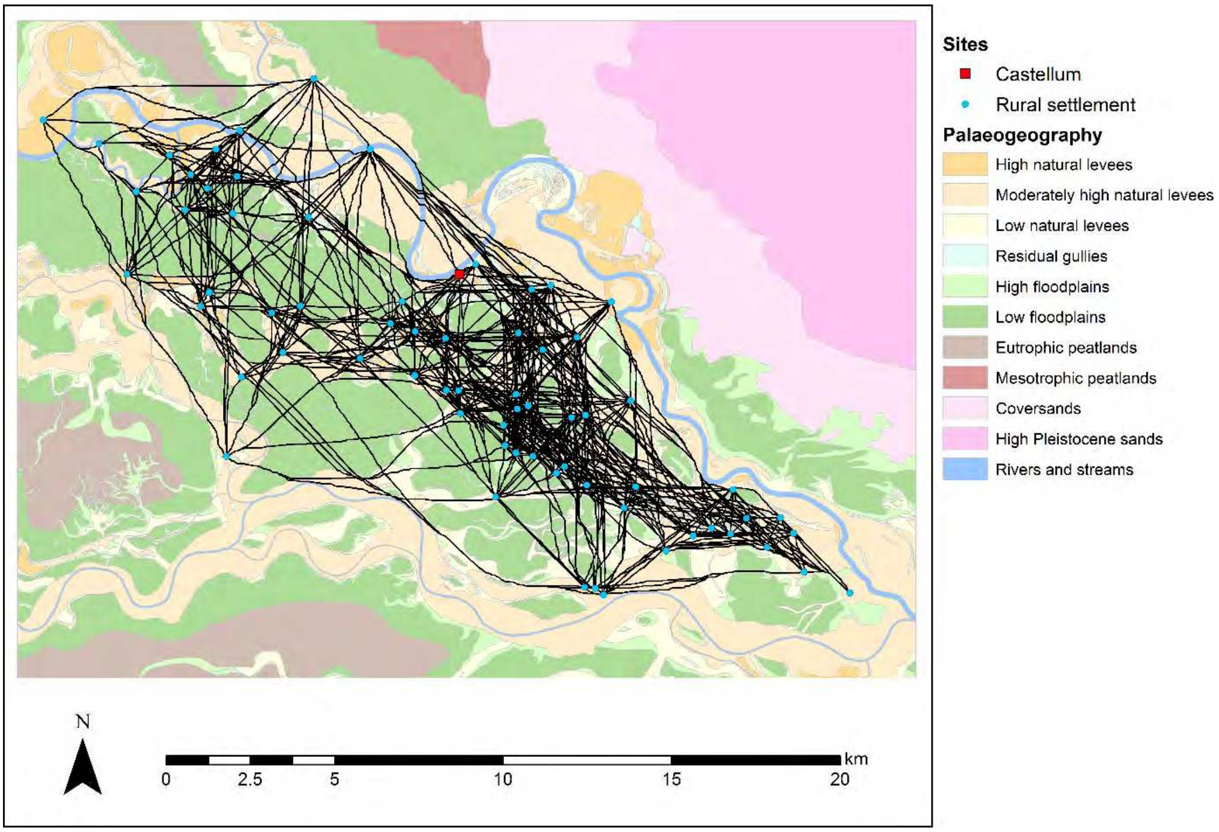


Figure 5.10. Modelled transport connections for local foot travel while carrying a load of 40 kg.

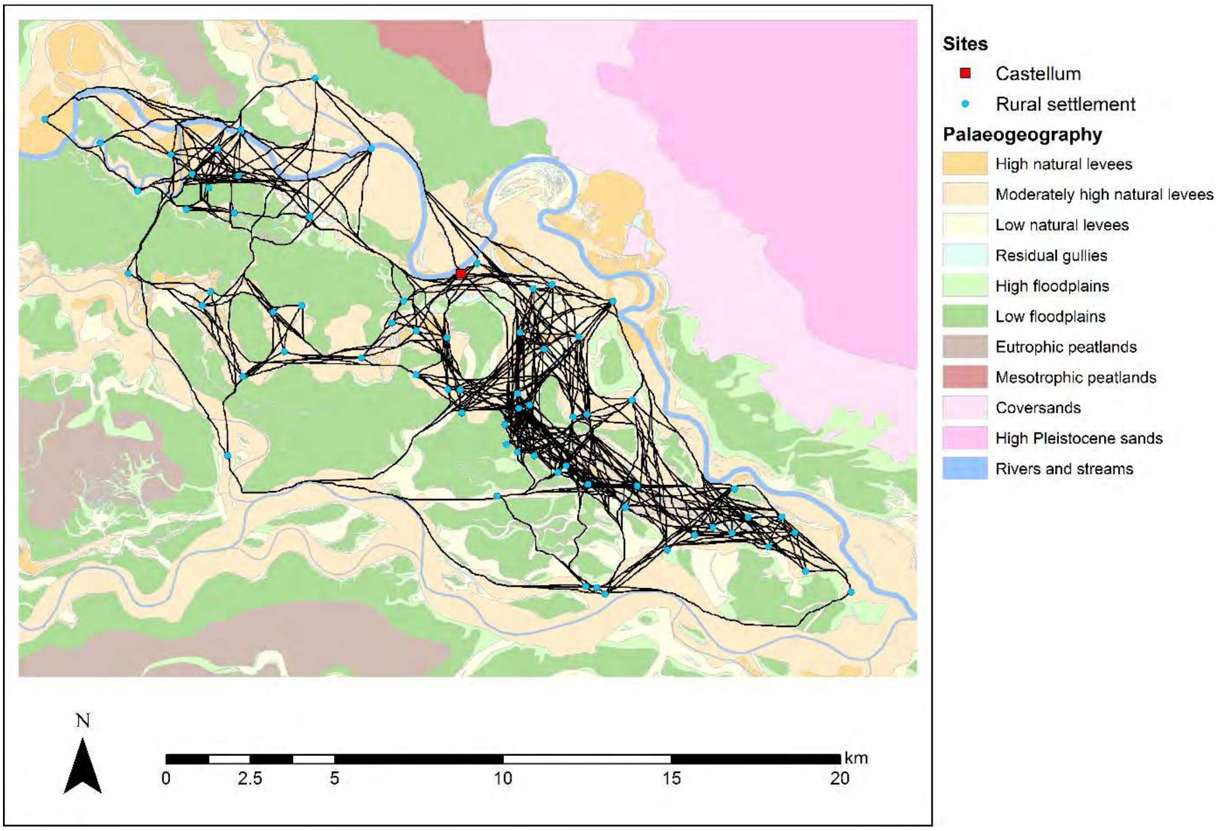


Figure 5.11. Modelled transport connections for ox-carts.

The distribution of route lengths over the palaeogeographic units for the modelled transport modes is given in Table 5.6 and Figure 5.12. The difference between the modelled routes of foot travel with various loads are very minor. Comparing mule- and ox-cart transport to foot travel, the use of the lower levees is halved and there is an even stronger decline in the use of floodplains. The distribution of route lengths indicate that the modelled transport connections are behaving as expected: the wetter parts of the landscape are less attractive for movement than the relatively higher and drier levees, and this effect is stronger for cart-based transport than for foot travel.

Palaeogeographic unit	W0		W20		W40	
	Length (m)	%	Length (m)	%	Length (m)	%
High natural levees	1,212,456	5.57%	1,198,712	5.63%	1,193,495	5.60%
Moderately high natural levees	15,742,728	72.37%	15,352,252	72.09%	15,372,890	72.19%
Low natural levees	2,080,329	9.56%	2,079,337	9.76%	2,059,514	9.67%
Residual gullies	284,391	1.31%	279,361	1.31%	280,547	1.32%
High floodplains	720,915	3.31%	705,131	3.31%	709,919	3.33%
Low floodplains	1,642,472	7.55%	1,612,020	7.57%	1,611,624	7.57%
Eutrophic peatlands	1,904	0.01%	1,904	0.01%	1,904	0.01%
Mesotrophic peatlands	0	0.00%	0	0.00%	0	0.00%
Coversands	0	0.00%	0	0.00%	0	0.00%
High Pleistocene sands	0	0.00%	0	0.00%	0	0.00%
Rivers and streams	66,525	0.31%	65,786	0.31%	65,486	0.31%
Total	21,751,720	100%	21,294,502	100%	21,295,381	100%

Table 5.6. Distribution of the total length of the modelled routes over the palaeogeographic units of the Kromme Rijn region, for foot travel with loads of 0, 20 and 40 kg (W0, W20, W40), mule-cart (MC) and ox-cart (OC) transport.

Palaeogeographic unit	MC		OC	
	Length (m)	%	Length (m)	%
High natural levees	1,245,758	5.34%	1,215,257	5.34%
Moderately high natural levees	20,225,478	86.72%	19,462,666	85.56%
Low natural levees	1,291,965	5.54%	1,462,402	6.43%
Residual gullies	205,134	0.88%	205,697	0.90%
High floodplains	201,882	0.87%	245,008	1.08%
Low floodplains	94,939	0.41%	100,036	0.44%
Eutrophic peatlands	0	0.00%	0	0.00%
Mesotrophic peatlands	0	0.00%	0	0.00%
Coversands	0	0.00%	0	0.00%
High Pleistocene sands	0	0.00%	0	0.00%
Rivers and streams	57,756	0.25%	55,855	0.25%
Total	23,322,912	100%	22,746,921	100%

Table 5.6. (Continued)

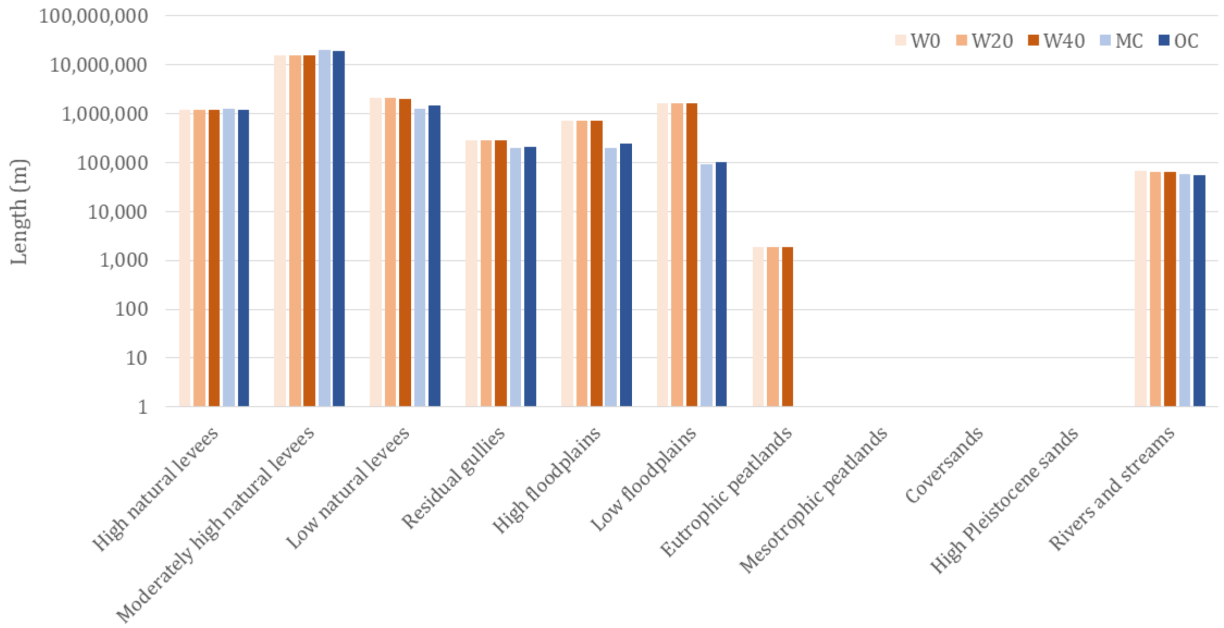


Figure 5.12. Distribution of the total length of the modelled routes over the palaeogeographic units of the Kromme Rijn region, for foot travel with loads of 0, 20 and 40 kg (W0, W20, W40), mule-cart (MC) and ox-cart (OC) transport.

Little is known about the infrastructure of local-scale transport, and this is likely largely due to the fact that the majority of local-scale movement occurred over mere routes rather than physically constructed roads (Willems 1986, 63–64). The only land-based transport infrastructure for which much archaeological evidence is available in the Dutch river area (excluding local infrastructure such as bridges across streams that are few and far between; e.g. Roymans 2007; Roymans and Sprengers 2012) is the military road, that connected the *castella* along the Rhine. Vos (2009) has made a reconstruction of the military road in the Kromme Rijn region, as well as an interpretation of secondary routes in the direct hinterland, largely based on assumptions rather than archaeological evidence. It is interesting to compare this reconstruction based on expert-judgement to the transport routes modelled in this study. Figure 5.13 shows the reconstruction by Vos (2009, 45) superimposed on the modelled ox-cart routes. What becomes immediately clear is that while there are some routes that follow the general path of the military road, the largest concentration of routes follow a more southern course, and actually quite closely align with the assumed secondary routes. The military road thus seems to be largely peripheral to the majority of local-scale interactions.

It is relevant to note that the modelled routes are based on a site dataset of the Early Roman Period A, and thus precede the construction of the military road. For the location of the military road, the first conclusion is that its role for potential routes of local-scale transport was not considered important. It is thus more likely that other factors governed its location, such as the control of movement over the river and a quick movement of troops between *castella*. This is not a surprising conclusion and the latter factors have often been mentioned in earlier archaeological research. However, it is more interesting to see if the construction of the military road played a role in changing the potential local-scale transport connections in later time periods. Figure 5.14 shows the modelled ox-cart routes for the Middle Roman Period A. The general conclusion is the same as for the earlier period: the military road lies largely outside the modelled local-scale transport connections, and is not important for interactions between rural settlements, as well as interaction between the rural and the military population.

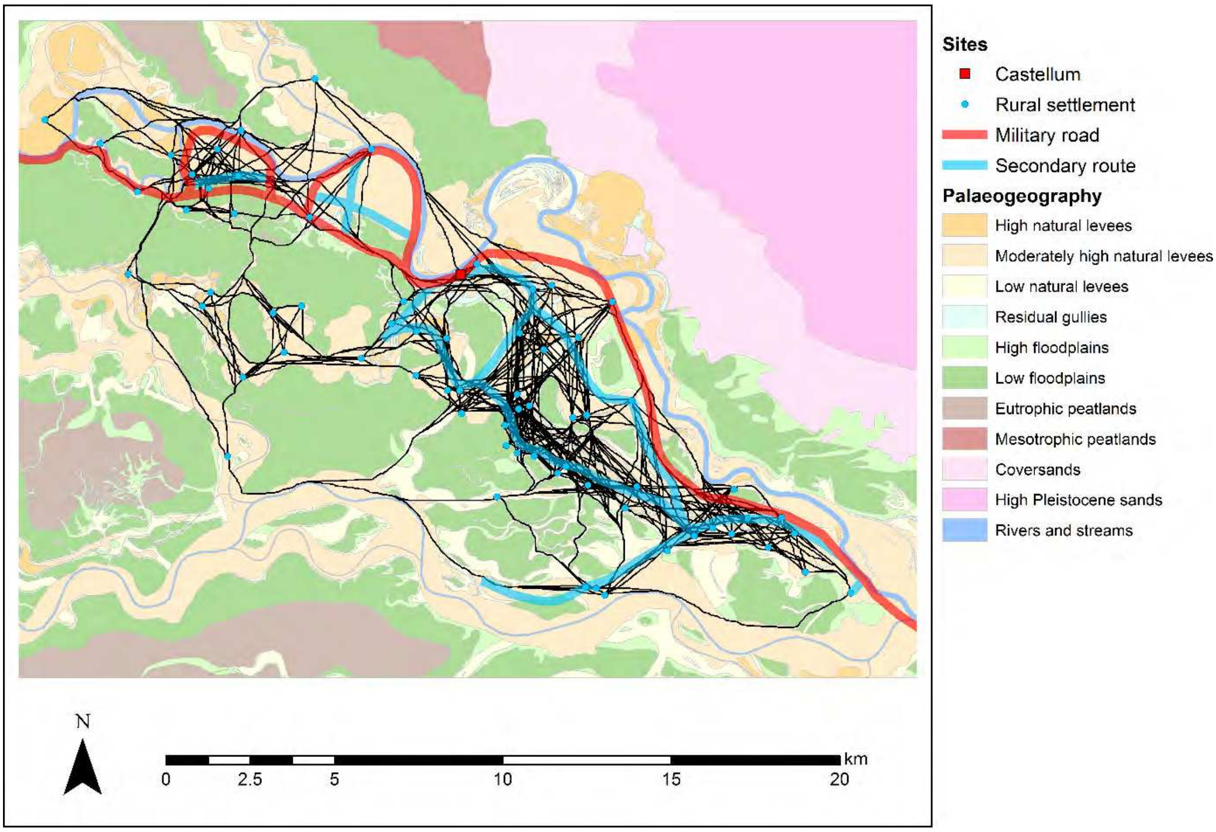


Figure 5.13. Comparison between the expert-judgement-based reconstruction by Vos (2009, 45) to the modelled transport connections for ox-carts for the Early Roman Period A.

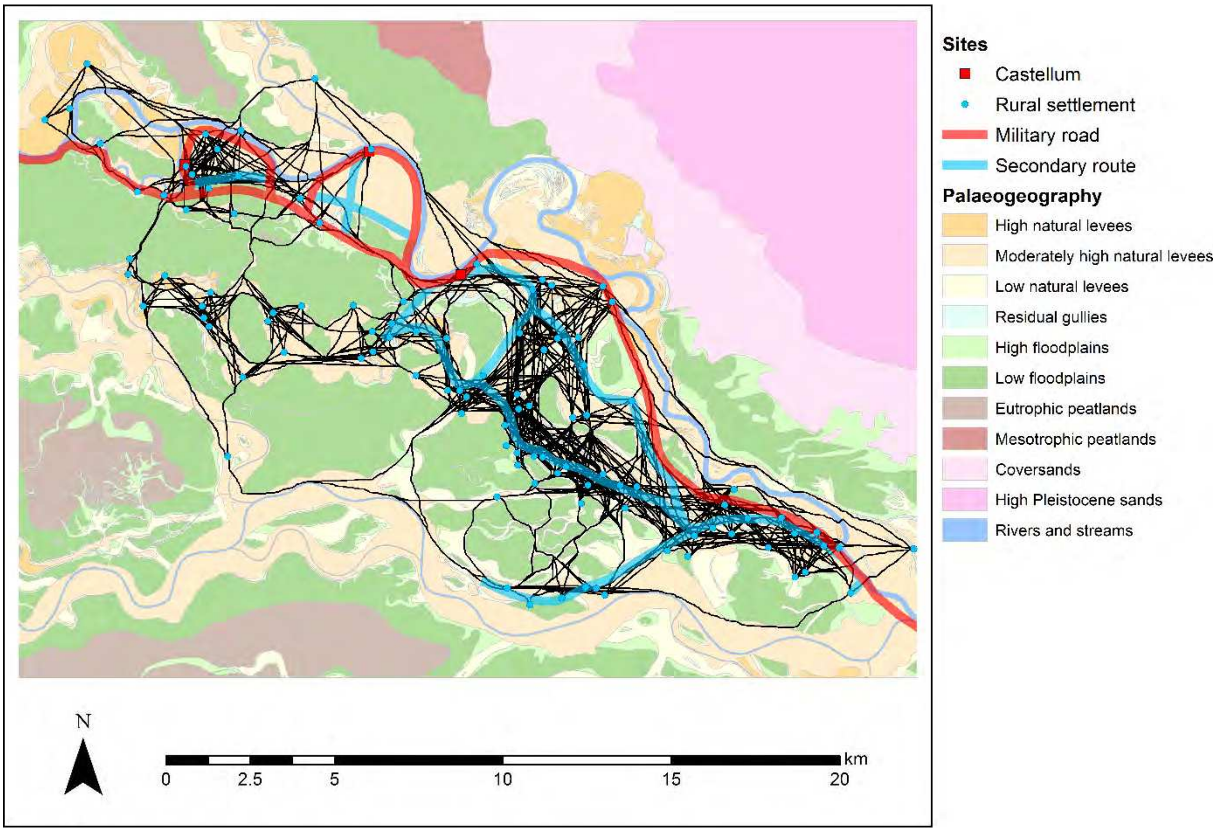


Figure 5.14. Comparison between the expert-judgement-based reconstruction by Vos (2009, 45) to the modelled transport connections for ox-carts for the Middle Roman Period A.

5.3.2 Modelling multimodal transport connections

Multimodal transport connections in this study mean connections that make use of both land-based and water-based transport modes. The methodology of LCP modelling of multimodal transport connections has been detailed in section 5.2.4. The basic principle is that movement in the downstream direction of rivers is faster than in the upstream direction, as can be seen in Figure 5.15, showing the travel time when using ox-carts with optional dugout transport moving away from the *castellum*.

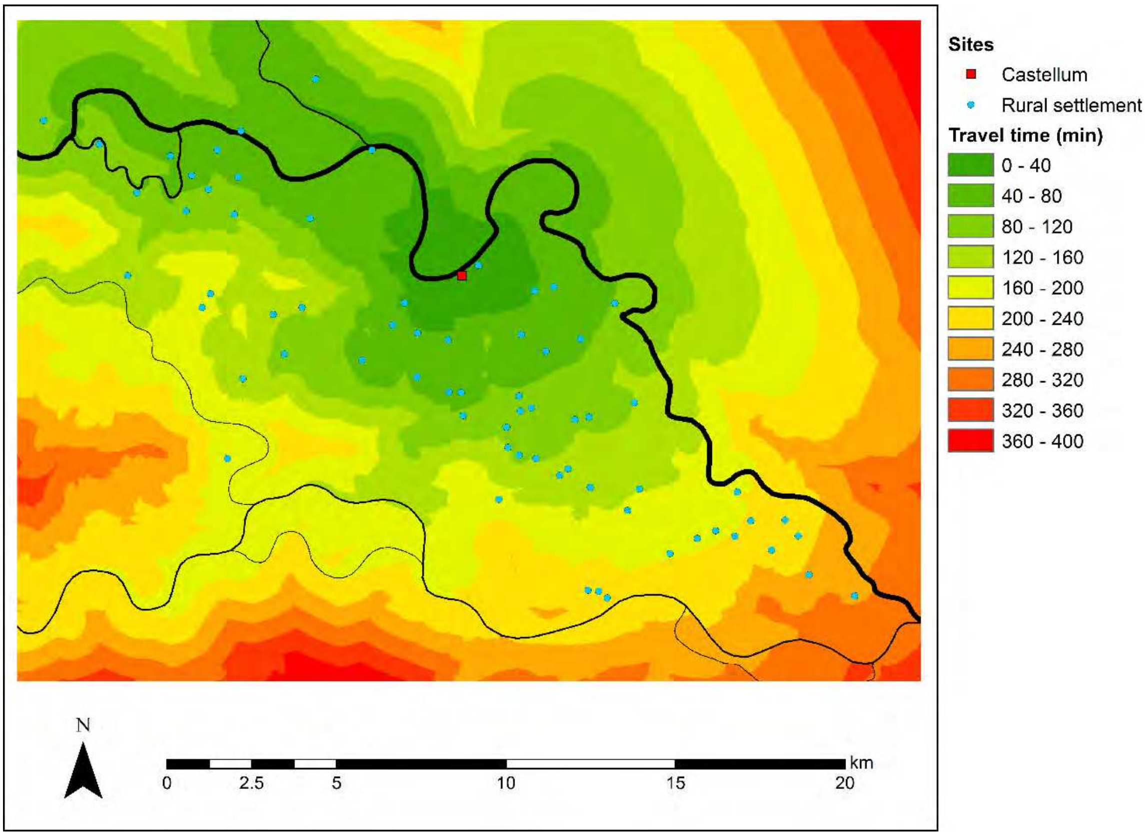


Figure 5.15. Travel time when moving away from the castellum*, based on ox-cart transport with optional use of dugouts. The fort is chosen for this figure simply because it is on the Rhine and roughly in the middle of the research area. This figure is not intended to demonstrate a 'central place' function.*

The resulting routes for ox-cart transport with optional dugout transport are shown in Figure 5.16. There is a single concentration of routes following the northern shore of the Rhine river, as well as a band of routes following the Lek and Hollandse IJssel rivers along the southern and western edges of the research area. The only exception is the large meander bend just northeast of the *castellum*, where movement over water appears to happen in two discrete instances over a single journey. Apparently the time costs of transferring between land- and water-based transport modes twice is lower than the time it would take following the entire river bend. This is an artefact of the modelling methodology, as multiple transfers are of course not entirely realistic from an archaeological point of view since dugout transports are not readily available at all places along the rivers, and a strategy of multiple load transfers would likely be considered too inefficient. Ideally, modelling transport connections that include transfers between modes would make use of specific places where such a transfer would be possible (i.e. a dock or quay). However, especially for local-scale transport using dugouts, it is largely unknown where such transfer places in the Dutch river area would be, and also if such a place would be a hard requirement for dugout transport or that in some circumstances a non-artificial landing place is also sufficient. The methodology followed here thus likely does not always result in the most realistic routes, but due to the lack of (archaeological) information that would be able to solve these problems, there is not a readily available solution.

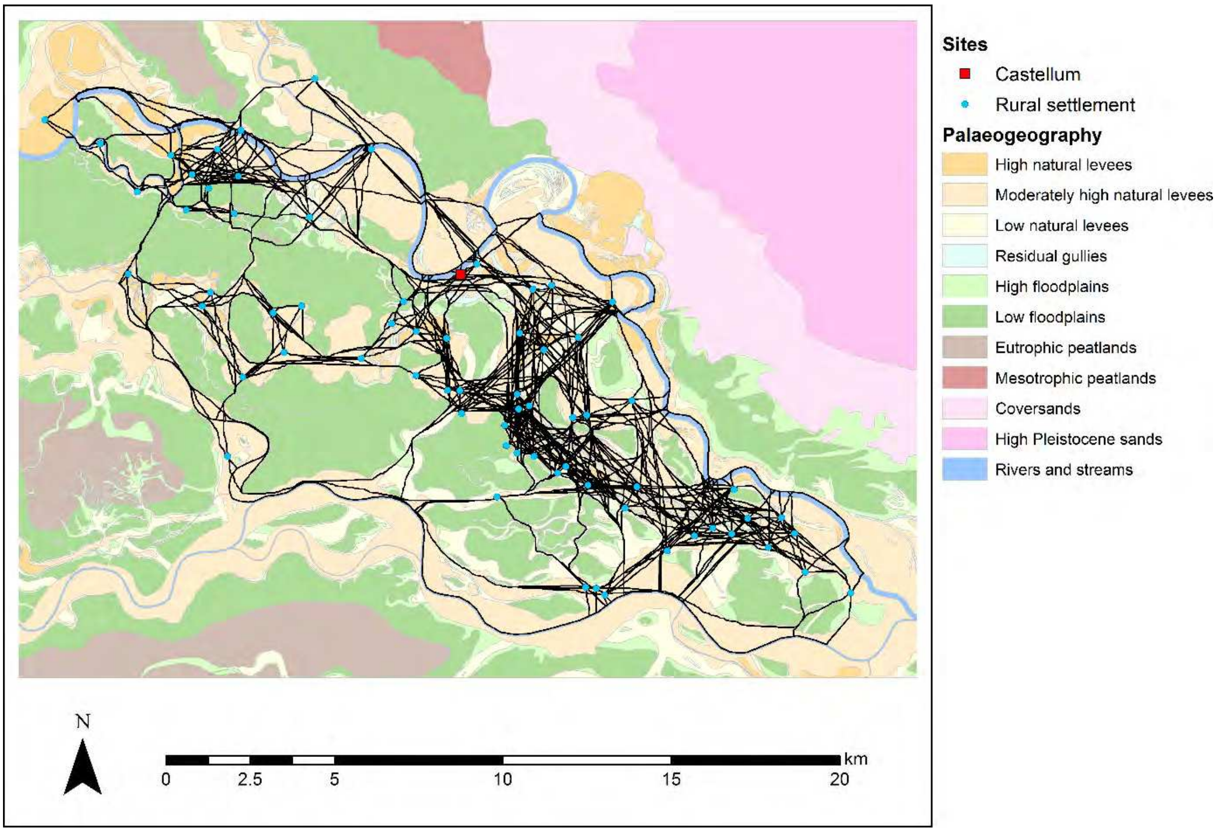


Figure 5.16. Modelled transport connections for ox-carts with optional use of dugouts.

The preferential movement over water is also seen in the distribution of route lengths over the defined palaeogeographic units of the Kromme Rijn region, shown in Table 5.7. The total length of the routes of ox-cart transport with optional use of dugouts is much longer than that of regular ox-cart transport, but this is due to the fact that the former calculates two routes between each pair of sites rather than one, since the inclusion of water-based transport makes the direction of movement relevant. Movement over rivers has a rather large share of 11.8%, but the majority of movement still occurs over the levees rather than water. This is likely due to the location of the rivers: they appear to be largely peripheral to the sites in this region, i.e. they are located around the edges rather than the centre. Thinking further about the Dutch river area as a whole, the general direction of the flow of rivers is in the east-west direction, whereas a fair share of movement is primarily in south-north direction (or vice versa), particularly when moving from rural settlements in the hinterland towards one of the military sites.

Palaeogeographic unit	OC		OC + D	
	Length (m)	%	Length (m)	%
High natural levees	1,215,257	5.34%	3,360,596	6.03%
Moderately high natural levees	19,462,666	85.56%	41,570,096	74.59%
Low natural levees	1,462,402	6.43%	3,264,230	5.86%
Residual gullies	205,697	0.90%	309,443	0.56%
High floodplains	245,008	1.08%	359,488	0.65%
Low floodplains	100,036	0.44%	308,169	0.55%
Eutrophic peatlands	0	0.00%	0	0.00%
Mesotrophic peatlands	0	0.00%	0	0.00%
Coversands	0	0.00%	0	0.00%
High Pleistocene sands	0	0.00%	0	0.00%
Rivers and streams	55,855	0.25%	6,561,677	11.77%
Total	22,746,921	100%	55,733,699	100%

Table 5.7. Distribution of the total length of the modelled routes over the palaeogeographic units of the Kromme Rijn region, for regular ox-cart (OC) transport and ox-cart transport with optional use of dugouts (OC + D).

5.3.3 Uncertainty in modelling transport through least-cost paths

As with many computational approaches in archaeology, there is always a degree of uncertainty in the results that can be caused by a number of sources. The uncertainty in modelling transport connections through LCP modelling can be the result of uncertainties in the palaeogeography that forms the basis for establishing costs of movement, the chosen method and parameters for calculating those costs, the chosen software for calculating the LCPs, and the site dataset from which the source and destination of the LCP are derived. Some of these aspects have been discussed in other studies: Gietl *et al.* (2008) have discussed the differences between the results when using various software packages; Herzog (2013d) has compared various methodologies for calculating hiking costs (particularly for slope-based studies); and Herzog and Posluschny (2011) when calculating LCPs with slope-based costs have introduced random variations in the digital elevation model to test the effects of uncertainty in the source of costs.

Uncertainty is thus undoubtedly deemed important by researchers in computational archaeology, and the above-mentioned studies have already provided valuable discussions that need not be repeated here in full. Two aspects of uncertainty will be discussed here: firstly, the aspect of uncertainty in the site dataset, from which the source and destination for a LCP are retrieved. Secondly, the aspect of uncertainty in the palaeogeographic reconstruction.

The uncertainty in the site dataset can be subdivided into two parts, namely the locational accuracy and the chronological accuracy of sites that are included in a LCP. With regards to chronology, this boils down to the basic question whether or not the sites on either end of the LCP are contemporary or not. Chronological accuracy has already been discussed in Chapter 3, and thus will only be treated here briefly: by using the approaches outlined by Verhagen *et al.* (2016b), the site dataset can be filtered to only include those sites that are above a certain threshold of reliability concerning their chronological information. For example, to illustrate the results of LCP modelling in the previous sections, the site dataset was filtered to only include sites that are dated to the Early Roman Period A based on at least a 50% probability of having a minimum number of 10 finds in that period. It is important to remember that this does not result in a 'complete' dataset of that period, since some sites may be excluded that in reality date to that period but simply have not enough finds associated with them. Even so, for this study the possible exclusion (or erroneous inclusion) of sites only becomes an issue when constructing a network of potential transport connections based on the modelled routes, which is the topic of Chapter 6 and therefore will be discussed there further.

Regarding locational accuracy, the potential error in LCP modelling lies in the possibility that a site is given certain x- and y-coordinates in the site dataset that poorly reflect its location in reality. Verhagen *et al.* (2016b, 310–11) briefly discuss locational uncertainty and state that the majority of observations have a precision of 10 m, and hardly any are less precise than 100 m. These observations are then grouped together into a site when they are within a range of 250 m of the centre of the site, and that centre is determined either as the observation with the largest number of finds or through more direct information (e.g. excavation). Although the method of establishing the centre of the site itself can be questioned, the maximum error when assuming the correctness of this methodology is thus in most cases not greater than 100 m (the error of the observation with the largest number of finds). Comparing that for example to the average length of routes of regular foot travel in the Kromme Rijn region in the Early Roman Period A, which is 9.27 km, the maximum margin of error due to locational inaccuracy is on average only about 1%. Considering that the Kromme Rijn region is a relatively densely inhabited area, average path lengths in other regions would be even higher, resulting in an even smaller error in comparison.

This leaves the uncertainty that resides in the palaeogeographic reconstruction. Sources of uncertainty have already been identified in Chapter 2 (section 2.4), and include post-Roman fluvial activity, drift sand formation, peat extraction, urban developments and other anthropogenic interferences in the landscape. Additional differences in reliability of the palaeogeographic reconstruction arise from the variation in scales of the available source datasets. A tentative uncertainty map for the Dutch river area has been developed in that section, that can be used to identify the reliability of the reconstruction for certain areas, which has its effect on further modelling and analysis, including the calculation of LCPs. The remainder of this section will focus on one specific case already mentioned in section 2.4 to illustrate the effects of uncertainty on LCP modelling, and that is the unknown extent of peat cover in the Roman period.

For this exercise, the peat cover of the Kromme Rijn region will be arbitrarily 'maximised' to cover the majority of the lower lying floodplains, as well as some of the smaller and lower levees. The underlying assumption for this extra peat cover is that it has either been buried by floodplain deposits or disappeared through cultivation and/or excavation in post-Roman time periods. The resulting LCPs of regular ox-cart transport are shown in Figure 5.17. Comparing this to the modelled ox-cart transport connections in the original palaeogeography, shown in Figure 5.11, some notable differences appear. The additional peat cover in the southern half of the Kromme Rijn region results in less crossings of the lower lying areas (due to the covering of smaller levees that traverse these areas) and a concentration of paths on the levees that remain. In the north-western quarter however, the addition of a peat cover over one smaller levee that formed a bridge in the original palaeogeography now results in a number of crossings over the newly added peatlands. Apparently this crossing of the lower lying areas was such an efficient route compared to the longer detour that it is maintained even when the costs of movement are raised through the addition of peat.

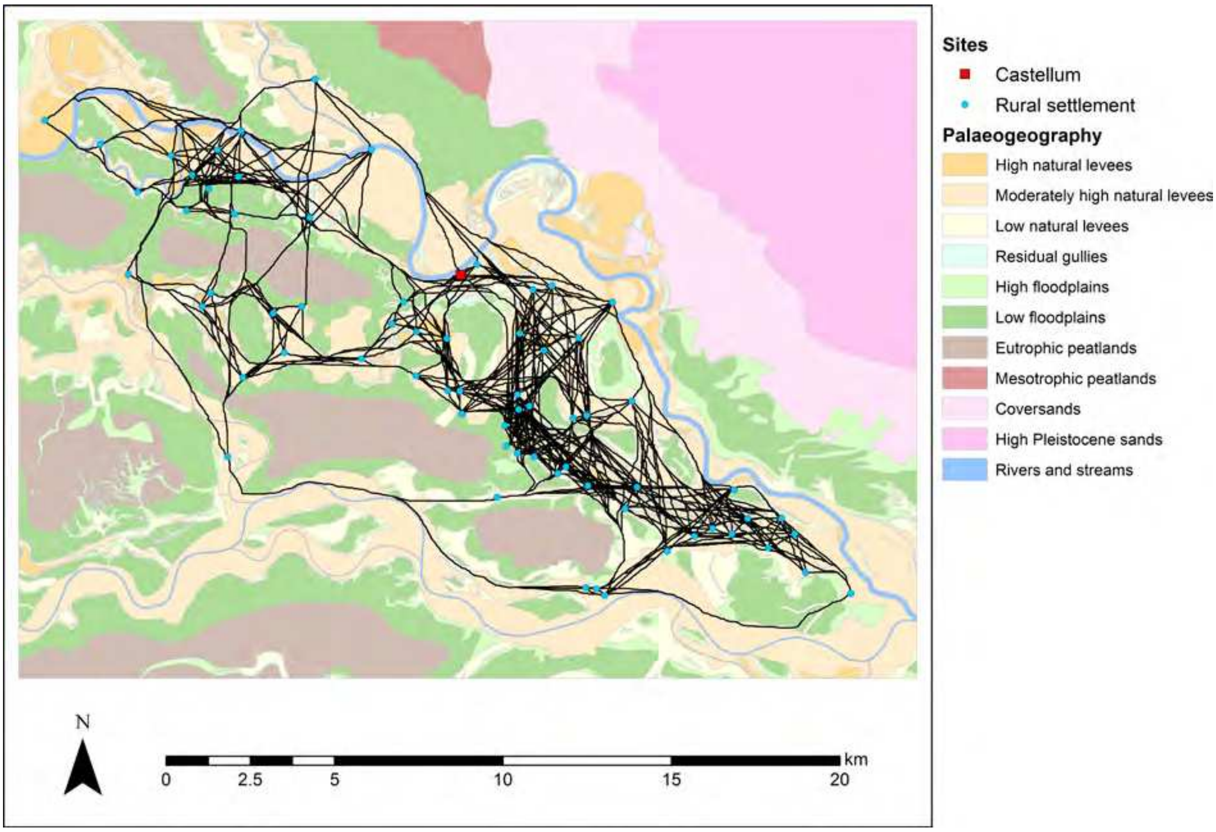


Figure 5.17. Modelled transport connections for ox-carts over an alternative palaeogeography where peat cover is 'maximised'.

Following the findings outlined above, the uncertainty in palaeogeographic mapping can undeniably play a role in calculating LCPs, but the extent to which this happens is very dependent on the specific local palaeogeography. In one instance, routes shifted to the remaining levees, while in another the routes generally continued to follow their original course as any detours were not efficient enough in terms of modelled travel time. It is thus important to keep in mind that uncertainty is present in the palaeogeographic reconstruction, established in a tentative uncertainty map in section 2.4, but it cannot be directly incorporated into LCP calculations since its exact impact is unpredictable and dependent on each local situation.

5.4 Conclusion

The modelling of transport connections presented in this chapter has been quite successful, in terms of understanding the interaction between movement and the natural environment, and the realisation of that interaction in the construction of LCPs. There are marked differences between the modelled routes of foot travel and animal-drawn carts in terms of where people move using these modes, and a further variation is introduced with the use of dugouts. However, the modelling of LCPs of foot travel could be performed with more reliability based on a stronger tradition in physiological (and archaeological) research on movement on foot, whereas animal-based and water-based transport modes had to rely on fewer and less compatible sources to the situation of the Dutch river area (e.g. in terms of terrain factors for carts or the influence of rivers on dugouts).

Within categories of foot travel or cart-based transport there are further differences in terms of travel time. This will become important when thinking about networks of transport, where time plays a role in deciding which of the modelled transport connections are part of the network and which are not. However, despite being able to make preliminary assertions based on the modelled routes such as that the Roman military road (the primary infrastructural feature that we know of) plays no role in local-scale transport connections due to its peripheral location in this case study of the Kromme Rijn region, potential transport connections modelled through LCPs do not readily tell us anything about the functioning of transport in the Roman Period when it concerns questions such as the movement of surplus production from the rural settlements and the provisioning of the Roman military population. This requires a further interpretation and analysis, which will be performed in the context of networks of transport as has been mentioned before, and this is the topic of the following chapter.

6 Transport networks in the Dutch part of the Roman *limes*

6.1 Introduction

6.1.1 Network reconstruction in Roman archaeology

Transport is an important factor in the structuring of the spatial and economic relations between the local population and military population of the Dutch part of the Roman *limes*. However, as has been alluded to in the previous chapters, investigating a single transport connection between two places does not immediately allow for larger interpretations regarding the socio-economic structure of the region. Transport links must therefore be considered as part of transport networks in which individual entities (e.g. settlements) may play varying roles. An important part of the project is thus to reconstruct transport networks in a way so that they can be used for analyses that are meaningful for archaeological hypotheses. There is clearly more than one way to approach this, and this research by no means intends to present an exhaustive discourse on Roman transport network reconstruction.

Roman network reconstruction is traditionally and understandably linked with the study of Roman roads. This can be attributed to the many sources that are available to study them, including historical sources such as the Antonine Itinerary, the Ravenna Cosmography or the Peutinger Table, as well as archaeological material evidence. In the Netherlands, research and discussions on uniting the historical sources with the archaeological and (physio)geographical reality have already taken place with some frequency since the first half of the 20th century (e.g. Blok and Byvanck 1929, 13–40; Kroon 1935; Stolte 1938; 1959; Modderman 1949c, 72–76; 1952). The goal of these early investigations in the first place was to locate the routes of the Roman roads that are described in the historical sources, with an extra implicit goal of finding evidence for the relation of the Roman roads with the (modern) physical environment (Modderman 1952, 28). The problems herein are still not sufficiently detangled and thus relevant for study even today, as is evidenced through publications by Joosten (2003), Buijtendorp (2010, 714–21), Van der Heijden (2011; 2016) and Verhagen (2014).

However, research on this subject only pertains to (the infrastructure of) potential routes of transport on the regional to imperial scale, and the resulting network often does not extend beyond the so-called 'northern' and 'southern' routes running between the modern German border and the North Sea that are described in the Peutinger Table. The spatially explicit investigation of interactions outside the main Roman road systems has been carried out less frequently. Recent examples are the research on the provenance of construction wood (Domínguez-Delmás *et al.* 2014), the inland navigation of ships (Jansma *et al.* 2014b), and the long-term persistence of long distance routes (Van Lanen *et al.* 2016). On a more local scale Vos (2009, 45) attempted to reconstruct local roads in the Kromme Rijn region, a study which was also discussed in section 5.4.1. Other reconstructions of regional to local roads have also been made for the eastern Rhine-Meuse delta (Willems 1986, 67), the area around Nijmegen (Willems and Van Enckevort 2009) and in a more descriptive form for the area around Den Haag (Waasdorp 1999) and around Cuijk (Haalebos *et al.* 2002). However, due to the lack of archaeological material (except a few bridges across streams in the southern coversand area; Roymans 2007; Roymans and Sprengers 2012) not much else is known about the local scale of transport, i.e. transport that connected the small rural settlements to each other and to the military settlements.

6.1.2 Questions of transport in the Dutch *limes* area

Chapter 4 has established the boundaries of what is known and unknown regarding transport in the Dutch part of the Roman *limes*, and section 6.1.1 has presented the current spatially explicit knowledge of Roman networks of transport, both of which are mostly limited to networks of infrastructure. Generally speaking, transport that occurs on the supraregional scales is quite well understood due to the amount of archaeological and literary evidence available. However, much less is known about local-scale transport, including interaction between the rural and military population of the *limes* zone.

In principle, the Roman army aimed to supply their troops from the local territory, i.e. the direct vicinity of the fort itself. However, for the Rhine-Meuse delta, which is only sparsely occupied by local communities in comparison to the relatively large body of military personnel, this would likely mean that the entire hinterland should participate in the provisioning of the Roman army, in addition to the resources that are imported from outside the province. Based on an analysis of the available archaeological material, Groot (2008b) and Groot *et al.* (2009) conclude that settlements in the rural hinterland of the Dutch *limes* area produced a surplus of cereals, beef, horses, and wool for the market, and that especially in the Middle Roman Period some settlements specialised in the production of a particular good.

How the goods then actually flowed from the rural to the military population remains largely unknown. It is thought that initial contact between the two groups occurred through markets and urban centres (Bloemers 1990, 115); similarly the top-down distribution of goods such as pottery occurred through local markets and centres (Willems 1986, 421; Vos 2009, 228) and through travelling merchants (Tacitus, *Hist.* IV, 15; Heeren 2009, 185–86). Asides from the larger cities and towns (*vici*), Vos (2009, 229–30) suggests that the stone-built rural settlements and a handful of other rural settlements that are slightly larger than average play a role in this vertical distribution system. This hypothesis (i.e. some sites playing an intermediary role in the network) has potential to be tested using a network approach, for example by contrasting it against another hypothesis (e.g. goods moving directly from rural settlements to the *castella*).

Such a study also touches upon related questions, for example regarding the role of stone-built settlements in this network: if they were important in Roman transport systems, could their profitable position have played a role in them becoming stone-built? Another example are the *horrea* sites: Vos (2009, 256–57) suggests they could have been used as central gathering sites prior to the movement of goods to the market based on the disproportionate size for their local settlements, a hypothesis which can similarly be studied by imagining transport as networks. Many *horrea* have been found in the Netherlands, including a number in the southern Netherlands (Verwers 1999, 245–46), but within the research area only four large ones are known in rural settlements, and they are fairly concentrated in the central part of the Rhine-Meuse delta.

6.1.3 Outline of this chapter

Sections 1.4.6.5-1.4.6.6 in the introductory chapter have provided an overview of the field of network science and formal network analysis techniques. Section 6.1.1 presented some reflections on transport network reconstruction that has been done in the past in the Roman Period in the Netherlands, and section 6.1.2 detailed some of the main archaeological problems and questions that can be related to aspects of transport networks, in order to outline some hypotheses that can potentially be tested through the use of analytical techniques. From the following section onwards this chapter will delve deeper into the analysis of networks of local transport, by presenting the application of network science methods in a number of case studies on transport networks in the Dutch part of the Roman *limes*. The aim throughout these sections is thus not just to introduce network methodological concepts, but rather to firstly identify the archaeological and methodological needs - the problems and questions in the realm of transport networks in general and those of the *limes* in particular - and then attempt to find the right analytical methods to approach these.

The first study, contained in section 6.2, presents a comparison between different techniques that can be used for the construction of a network, using the local transport connections modelled with the least-cost path approach outlined in Chapter 5. The goal of this study is thus to find the network structure that best represents a network of potential local transport connecting the rural settlements to the military population in the Dutch part of the Roman *limes*.

Before applying formal network analysis methods to the constructed networks of transport, section 6.3 deals with the often overlooked aspect of uncertainty in network studies. It presents a robustness analysis that can be applied to strengthen the interpretation of the quantitative analysis of (transport) networks.

Section 6.4 presents two studies that apply formal network analysis techniques to approach the archaeological questions outlined in section 6.1.2. Firstly, it presents an analysis of the flow of goods from the rural to the military population, comparing two contrasting hypotheses: one in which the goods flowed directly to the forts and cities, and one where goods flowed through intermediary sites. Secondly, it presents an analysis of the role that stone-built rural settlements play in networks of local transport.

The final section 6.5 contains a study on continuity and change in transport networks. The first goal is to compare the application of the reinterpreted chronology associated with archaeological sites (section 3.4.2; Verhagen *et al.* 2016b) with the original chronology. Secondly, the study focusses on the development of local transport networks through time and discusses potential changes in the network in light of transitions known from the archaeological record (e.g. the Batavian revolt and the 3rd century border collapse).

6.2 Comparing network construction techniques[1]

6.2.1 Introduction

In Chapter 5 (section 5.2) the methodology for modelling transport routes using least-cost path techniques has been outlined. A following step is to construct networks of transport from these routes to allow for a more quantitative analysis. However, simply combining all of the modelled routes in a single network results in what is called a 'fully connected network', which is useless from an analytical purpose as all nodes in the network are egalitarian. From an archaeological perspective it is also not very realistic, since a route between two distant places is unlikely to go there directly and bypass all places that are on the way. This expectation is supported by studies on human navigation and wayfinding, which suggest that most journeys between two places actually consist of multiple shorter journeys between places that travellers know are on the way and that are part of their cognitive map (Murrieta-Flores 2010, 260–61). In an earlier article published in the context of this project (Groenhuijzen and Verhagen 2015), which is also treated

[1] The content of this section was published earlier in slightly modified form as **Groenhuijzen, M. R., and P. Verhagen. 2017. "Comparing Network Construction Techniques in the Context of Local Transport Networks in the Dutch Part of the Roman Limes."** ***Journal of Archaeological Science: Reports*** **15: 235–51. doi: 10.1016/j.jasrep.2017.07.024**, the only difference being the modified introduction, a shorter introduction on the datasets, and minor rephrasing. Research design by MG and PV; data provided by MG and PV; analysis by MG; discussion and conclusion by MG.

in section 6.6.1, no further consideration was given to the choice of techniques to construct a network from the dataset of routes, rather choosing between simple and arbitrary thresholds of 20, 30 and 60 minutes for modelled transport routes to be included or excluded in the network, based on the aforementioned principle.

In contrast, Rivers *et al.* (2013) in a study on centrality in networks of interaction (thus not limited to transportation) of the Middle Bronze Age southern Aegean argue that the choice between different network structures is in fact relevant, and that our understanding of the archaeological record we aim to represent should be the basis of deciding which network construction technique is most suitable (see also Evans 2014; Rivers 2014). They included a spatial component in the form of homogeneous geodesic distances between various islands in the Aegaen, while the actual time or effort to undertake such voyages was assumed to be directly proportional to distance, and land-based travel was given a uniform friction coefficient. These assumptions were not really a problem since most travel in the study of Rivers *et al.* (2013) occurred over water. Inspired by this study but aiming to extend the methodological concepts by using heterogeneous travel times between places, this study intends to compare different network construction techniques and evaluate them based on the archaeological representation we aim to achieve: that of a potential local provisioning system connecting rural settlements with the military population in the *castella* of the Dutch part of the Roman *limes*.

6.2.2 Data

For the purpose of this study, the site dataset will be filtered to only include those sites interpreted as settlements and that have a 50% or greater probability of having 10 or more finds dating to the Middle Roman Period A (section 3.4.2; Verhagen *et al.* 2016b). This selection of sites of course does not equal the entire range of what was present, since the method only selects those sites with datings of which we are fairly confident. The reasons why this specific period was chosen are that a large number of *castella* were occupied during this period and the Roman frontier was well established since the decision by emperor Claudius to permanently suspend Roman expansion across the Rhine in 47 CE. It is assumed that settlements north of the Rhine did not participate in the surplus production for the Roman army during the Middle Roman Period (Van Dinter *et al.* 2014, 23; although this may be an oversimplification for the Middle Roman Period B, see Van der Velde 2011, 134–36) and are thus not included as a regular part of modelled networks representing a local provisioning system. The resulting dataset contains 524 archaeological sites, of which 484 are rural settlements, 18 are large civil settlements (*vici* and towns), 21 are *castella* and one is a *castra*. The 16 *castella* located along the Rhine in the Netherlands were used for the analysis in this study (Fig. 6.1). The dataset of transport connections modelled using least-cost paths will now only include those for walking while carrying a load of 20 kg, in order to focus on the comparison of network construction techniques.

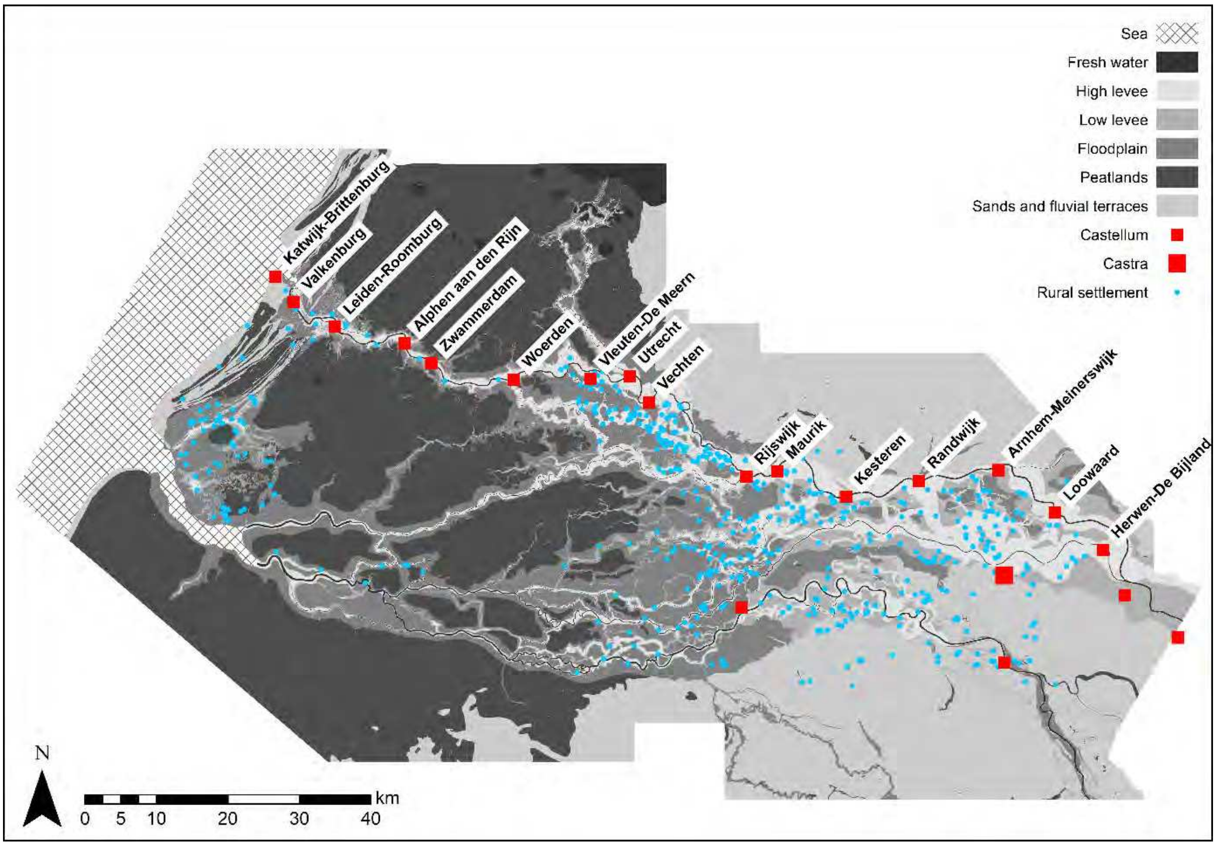


Figure 6.1. Palaeogeographic map of the Dutch part of the Roman limes. The 16 castella along the Rhine in the Netherlands that will be used for the analysis are labelled with their commonly used modern toponyms.

6.2.3 Network construction techniques

A number of network construction techniques will be discussed in this study, namely maximum distance networks, proximal point networks, the Delaunay triangulation and Gabriel graph, as well as a network based on an efficiency criterion. It must be noted that the Delaunay triangulation and Gabriel graph are simple subsets of the completely connected network, whereas the maximum distance, proximal point and efficiency networks are constructed on the basis of an assumed agency to create a connection between two places or not, as will be illustrated for each network separately in the following sections. With the exception of the Delaunay network, the execution of each of the construction techniques was carried out using Python scripts, which are detailed in Appendix 3.

6.2.3.1 Maximum distance networks

Maximum distance networks (Fig. 6.2) are probably the least complex in terms of construction. These networks only include links that are below a certain threshold of the established cost unit. Rivers *et al.* (2013) use maximum distance networks with an arbitrary cut-off distance D, expressed in kilometres, to represent the limitations that maritime technology imposes on single sailing journeys in the Middle Bronze Age southern Aegean. Using this principle, it was also possible to investigate how the network develops through the improvement of sailing technologies and the resultant increase in D. The maximum distance network follows a special variation of the deterrence function $f(d_{ij})$, the expression that can be used to convert the costs of a journey between site i and j of distance d to a likelihood of making that journey. In this instance, that likelihood is 1 if $d \leq D$ and 0 if $d > D$.

In our previous study on local transport in the Dutch *limes*, we have used the maximum distance criterion expressed in units of time in order to build networks from the modelled least-cost paths (Groenhuijzen and Verhagen 2015). Although the threshold chosen ultimately remains arbitrary, the use of a maximum temporal distance is partly justified by studies on human navigation and wayfinding, which suggest that most journeys between two places actually consist of multiple smaller journeys between places that travellers know are on the way and that are part of their cognitive map (Murrieta-Flores 2010, 260–61). Related to transport networks that are modelled in this study, both the start and end of a journey as well as all possible places on the way are thus settlements. In this comparison, networks will be modelled using a D of 30, 60, 90 and 120 minutes.

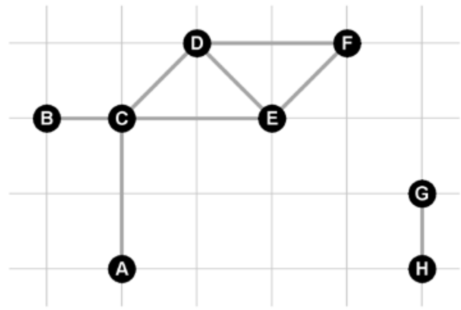


Figure 6.2. Schematic example of a maximum distance network (in Euclidian space) with D*=2.*

6.2.3.2 Proximal point networks

Proximal point networks (Fig. 6.3) were introduced by Terrell (1976) and further popularised by Broodbank (2000, 180–210). Commonly referred to as the proximal point algorithm (PPA), it is a gravity model based on the premise that a site more heavily interacts with its closer neighbours than with those that are further away. This is realised in the algorithm by letting each node in the network create an undirected link with a k number of its nearest neighbouring nodes, most commonly for a low value of k. Ultimately some nodes will connect to more neighbours than the defined value of k, by virtue of being a close neighbour to a larger number of other nodes. The algorithm is an ordinal variation of the exponential deterrence function, as the likelihood of a link being formed decreases when the distance between two sites increases.

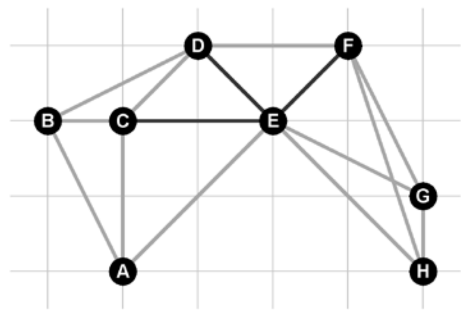


Figure 6.3. Schematic example of a proximal point network (in Euclidian space) with k*=3. As an example, the nearest neighbours of node E are highlighted in bold.*

Using the proximal point algorithm, some sites will naturally arise as central nodes by being better connected than others, and natural corridors and bottlenecks of flow in the network will become visible. Both Broodbank (2000) and Rivers *et al.* (2013) use geodesic distance to define the distance between nodes, stating that travel times between places across the southern Aegean, at least when looking over a time period of a year or more, can be considered uniform. However, the properties of the least-cost paths modelled in this study allow for the use of temporal distance rather than geodesic distance to model proximal point networks, as an attempt to more accurately represent the non-uniformity in travel times between places in a heterogeneous landscape such as the Dutch Rhine-Meuse delta. Proximal point networks in this study were therefore constructed using temporal distances to define the proximity between neighbours, and networks were compared using a k of 3, 5 and 7 neighbours.

6.2.3.3 Delaunay triangulation

In contrast to the previous network construction methods, Delaunay triangulations (Fig. 6.4) are more strongly rooted in mathematics than in social studies. It is the geometric dual of the more commonly known Voronoi diagrams or Thiessen polygons, which have been used in archaeology in research related to site catchments or territories (e.g. Bloemers 1980, 155, on Roman period *civitates* in the Low Countries; Vos 2009, 230, to study territories in a hierarchical settlement structure of a smaller case study in the Dutch *limes* zone). Delaunay triangulations are named after the work of Delaunay (1934) on the topic, and are network constructions with the property that each triangle ABC in the network does not have another node D in the circumcircle of triangle ABC. In contrast with the previously discussed construction methods, the presence or absence of links in the network is thus not governed by a so-called deterrence function; the distance between two sites does not play a role in determining if there should be a direct connection between the two.

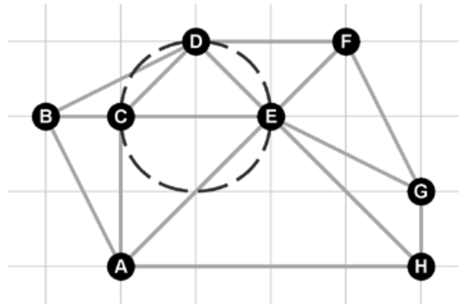


Figure 6.4. Schematic example of a Delaunay triangulation (in Euclidian space). As an example, triangle CDE is shown to be a part of the Delaunay triangulation since no other nodes are in its circumcircle.

In principle the Delaunay triangulation makes use of the Euclidian distance between nodes in the graph, which equals to the geodesic distance between sites in this study. There are some off-the-shelf implementations available for performing Delaunay triangulations, including one in the popular R package (R Core Team 2013; Barber *et al.* 2015), which was used in this study. While the temporal distances between places derived from the least-cost paths are thus not used in the construction of the network, they are assigned to the links in the Delaunay triangulation afterwards, in order to be used in the later analysis.

6.2.3.4 Gabriel graph

The Gabriel graph (Fig. 6.5), introduced by and named after Gabriel and Sokal (1969), belongs to a group of proximity graphs which have found some more use in archaeological applications (Brughmans 2010, 292–94; Jiménez-Badillo 2012). Rather than just considering the distance between two places, this group of graphs also considers the region around those two places to determine whether or not a link is part of the network. The specific property of the Gabriel graph is that two nodes A and B are linked only when there is no other node C in the circle of which AB is the diameter, which also makes it a subgraph of the Delaunay triangulation. Similarly, it is not governed by a deterrence function that determines if a link should be present according to the costs of that link. Given a Delaunay triangulation it is a relatively easy procedure to arrive at a Gabriel graph by evaluating each link in the triangulation for the aforementioned property.

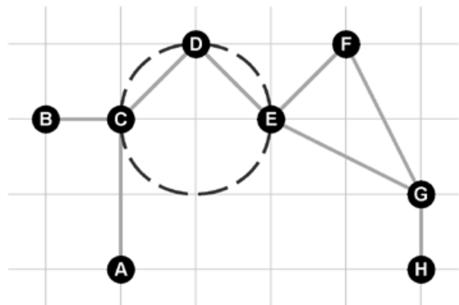


Figure 6.5. Schematic example of a Gabriel graph (in Euclidian space). As an example, link CE is shown not to be a part of the Gabriel graph since node D is on the circle of which CE is the diameter.

6.2.3.5 Delaunay triangulation and Gabriel graph in non-Euclidian space

One of the downsides of the traditional Delaunay triangulation and Gabriel graph is that they are both constructed on the basis of the geodesic distances between places. Considering the heterogeneity of the landscape of the Dutch river area, our preference would be to include the temporal distances derived from the least-cost paths, similar to the construction of the maximum distance and proximal point network. In this study an attempt was made to model a Delaunay triangulation and a Gabriel graph in this so-called non-Euclidian space, which was unsuccessful for the former but possible for the latter, as will be explained below.

Both the Delaunay triangulation and the Gabriel graph are based on principles that can be expressed in angles. For example, when the angle of node C with nodes A and B (∠ACB) is greater than 90°, by extension of Thales' theorem node C is found inside the circle of which AB is the diameter, on the basis of which it can be established that link AB is not part of the Gabriel graph. Such concepts also allow for the implementation of temporal distances between places, as we can for example calculate the angles of a triangle in our network based on three edges whose length is expressed in time. It would result in triangles with angles that are not necessarily the same as the angles of the corresponding Euclidian triangle based on geodesic distances.

In both the Delaunay triangulation and the Gabriel graph we essentially encounter three distinctive situations when using temporal distances to calculate angles, which we can relate to whether or not they abide to the geometric principles of either graph. The first and preferred situation is where the angles of a triangle can be calculated without problems and we can readily evaluate them further, because the cosine of all angles is between -1 and 1 (angles between 180° and 0° respectively; Fig. 6.6A-B).

In the other two situations we encounter imperfect triangles, which are artefacts of the use of least-cost path modelling. More precisely, the imperfections are the result of rounding errors in the construction of least-cost paths over a raster.

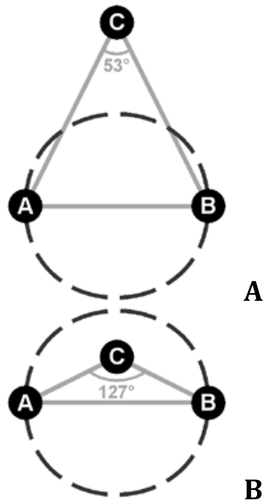


Figure 6.6 Principal behind constructing a Delaunay triangulation and a Gabriel graph in non-Euclidian space, schematically simplified to Euclidian space. The diameter circle related to the construction of a Gabriel graph is shown. A) Link AB is part of the Gabriel graph since node C is outside the circle of which AB is the diameter (∡ACB < 90°). B) Link AB is not part of the Gabriel graph since node C is inside the circle of which AB is the diameter (∡ACB ≥ 90°).

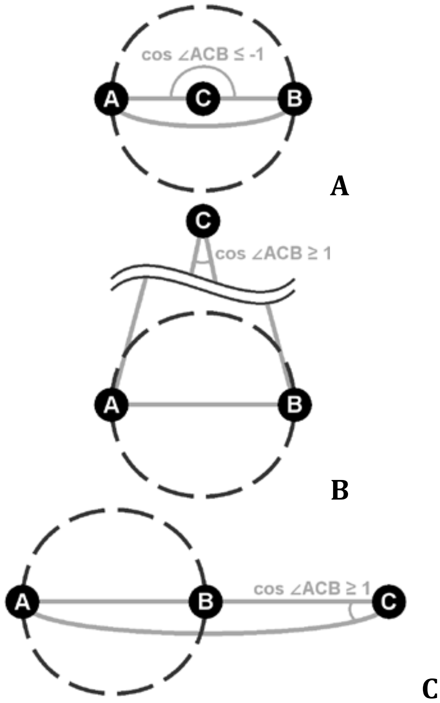


Fig. 6.7. Imperfect triangles in the construction of a Delaunay triangulation and a Gabriel graph in non-Euclidian space, schematically simplified to Euclidian space. The diameter circle related to the construction of a Gabriel graph is shown. A) The sum of |AC| and |BC| is smaller than |AB|, resulting in cos ∡ACB ≤ 1. As node C is inside the circle of which AB is the diameter, link AB is not part of the Gabriel graph. B) Node C is on the extrapolation of line AB, so that cos ∡ACB ≥ 1. As node C is outside the circle of which AB is the diameter, link AB is part of the Gabriel graph. C) Node C is so far removed from AB that cos ∡ACB ≥ 1.

The first imperfect triangle ABC occurs when the sum of |AC| and |BC| is smaller than |AB|, or expressed in terms of the angles, the cosine of ∠ACB is equal to or smaller than -1 (Fig. 6.7A). The second imperfect triangle occurs when the cosine of ∠ACB is equal to or greater than 1. This means that either |AC| or |BC| is greater than the sum of the lengths of the other two edges. Example are when node C is on the extrapolation of line AB outwards from nodes A and B (Fig. 6.7B), or generally when node C is very far removed from line AB (Fig. 6.7C). Such situations are theoretically impossible as the principles of least-cost paths state that the direct path between AB should be equal to or shorter than the path between AB over node C, but as stated above can occur due to the use of least-cost path modelling. How these imperfect triangles play a role in the construction of a Delaunay triangulation or a Gabriel graph will now be addressed for each technique individually.

The construction of a non-Euclidian Delaunay triangulation was attempted using an incremental flip algorithm (Guibas *et al.* 1992), which is a common and relatively efficient method to construct Delaunay triangulations. It iteratively builds the network by adding a node E (Fig. 6.8A), then splitting the triangle ABC that contains node E into three smaller triangles ABE, ACE and BCE (Fig. 6.8B). Over each outer edge of these three triangles it is evaluated if that triangle and the neighbouring triangle abide to Delaunay principles (e.g. ABD and ABE over edge AB), meaning that the sum of the angles that are opposite to the adjoining edge (e.g. ∠ADB and ∠AEB) should be smaller than 180° (Fig. 6.8C). If the sum is greater than 180°, the opposing nodes are in the circumcircle of their neighbouring triangle, meaning that the edge must be flipped to abide to Delaunay principles (Fig. 6.8D). This changes the triangulation structure, necessitating the newly created triangles to be evaluated again, and in that way an addition of a single node can result in multiple successive edge flips. Unfortunately this attempt to use the temporal distances as edge lengths, in order to calculate the angles that are necessary to check for Delaunay properties, ultimately became too complex. For example, in the situation of the first imperfect

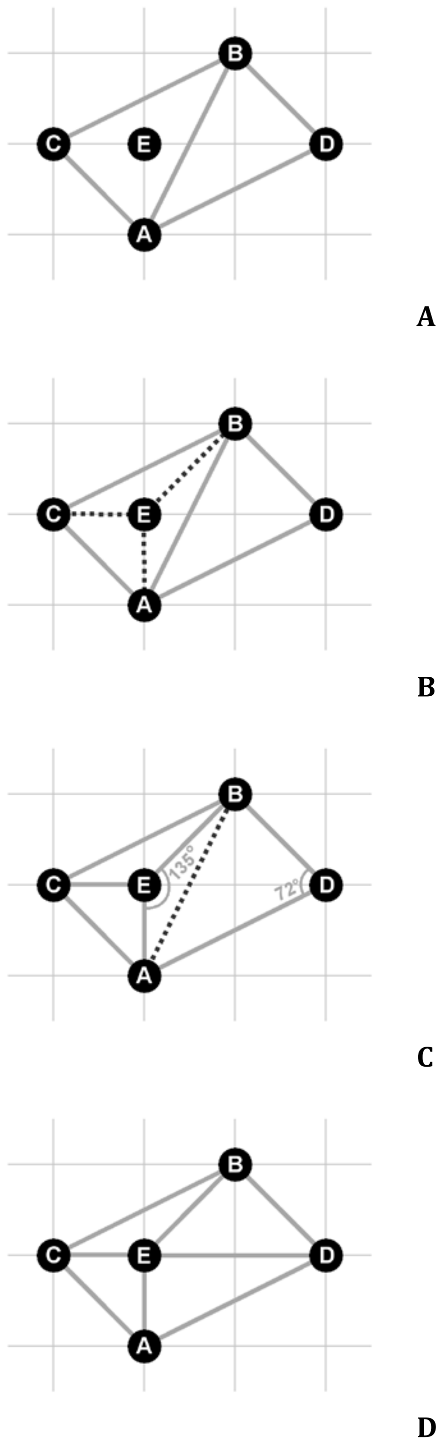


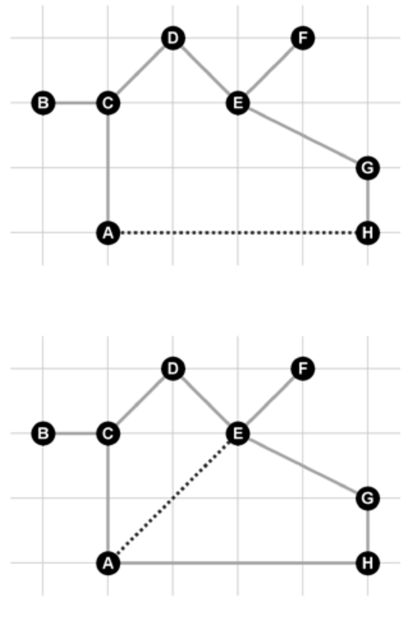
Figure 6.8. Steps of the incremental flip algorithm. A) Node E is added to the existing triangulation of nodes ABCD, and appears in triangle ABC. B) Triangle ABC is split between triangles ABE, ACE and BCE. Each triangle that neighbours another triangle is evaluated over the adjoining edge, in this case only triangle ABE with ABD. C) The sum of the angles ∠AEB and ∠ADB is > 180°, indicating that nodes D and E are in the circumcircle of the neighbouring triangle. D) Triangle edge AB is flipped to DE, and the new triangles now abide to Delaunay principles.

triangle ABC (Fig. 6.7A) it was impossible to assess to which side of link AB node C is located. In turn this makes it impossible to find out if another node D is inside the circumcircle of triangle ABC as that depends on which side the circumcircle is located. An alternative approach could be to construct non-uniform Thiessen polygons by calculating the cost distance raster for each site and then on the basis of that evaluate for each cell which site is closest, but considering the size of the dataset and the study area this would be rather time consuming. Since many of the sites that are neighbours in regular Thiessen polygons are likely to remain so in temporal Thiessen polygons, the Delaunay triangulations will also not differ much. For this reason, a non-Euclidian Delaunay triangulation was disregarded in this study.

However, the fact that the Gabriel graph is constructed on the basis of a simpler mathematical property makes it possible to construct such a graph in non-Euclidian space, by using the temporal distance between places instead of the geodesic distance. This was achieved by evaluating for each possible link AB if it is a part of the Gabriel graph, using the principle that all nodes C that are outside the circle of which AB is the diameter have an angle ∠ACB < 90° (Fig. 6.6A), and are inside the circle when ∠ACB ≥ 90° (Fig. 6.6B). In the latter case, link AB is disregarded from the Gabriel graph. When encountering the first imperfect triangle, node C must be in the circle of which AB is the diameter as the sum of |AC| and |BC| is smaller than |AB|, disregarding AB as part of the Gabriel graph (Fig. 6.7A). For the categories of the second and third imperfect triangles, node C is considered outside the circle of which AB is the diameter, as |AB| is too small in relation to the sum of |AC| and |BC| (Fig. 6.7B-C). The construction of a Gabriel graph in non-Euclidian space using the temporal distances between places could thus be completed successfully.

6.2.3.6 Efficiency networks

Lastly, efficiency networks are not a coined term in network science, but are rather a new idea based on earlier work in archaeological studies. Particularly, it is inspired by the methodology applied in a network study of urbanisation in central Italy (Prignano *et al.* 2016; later published in Fulminante *et al.* 2017). The general concept is that a network is 'grown' by adding links to the network in order to make it function more efficiently (i.e. to make it easier to travel over the network). The original methodology calculates for each unconnected pair of nodes the efficiency improvement when a link between that pair would be added to the network, which is realised by dividing the path length between the pair of nodes over the current network by the path length of a direct link between that pair. In the research by Prignano *et al.* (2016), the priority of links that would iteratively be added to the network was then established in two different ways, to explore the underlying mechanisms of the formation of communication networks: firstly, through so-called global estimation, selecting the link of greatest efficiency improvement over the entire set of links (mimicking coordinated



A

B

Figure 6.9. Schematic example of the construction of an efficiency network (in Euclidian space) according to the method of global determination. A) The minimum spanning tree as starting point, with link AH as the first addition in the efficiency network. B) Link AE is the second addition to the efficiency network.

decision making of a society in the construction of the network; Fig. 6.9A-B); and secondly, through so-called local determination, selecting a node randomly and then adding the link with greatest efficiency improvement related to that node (non-coordinated decision making; Fig. 6.10). The latter method results in a range of possible networks due to the randomness of links added, whereas the former always results in the same network.

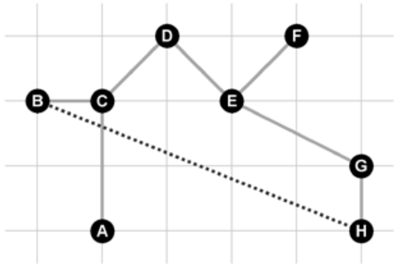


Figure 6.10. Schematic example of the construction of an efficiency network (in Euclidian space) according to the method of local determination. The minimum spanning tree is shown with link BH added as the first addition in the efficiency network, after node B was randomly selected to add its link with the greatest efficiency improvement.

This study will not apply a full replication of the original methodology, but will only use global determination of which link has the greatest efficiency improvement when added to the network. The method of local determination is not repeated, as the dataset is simply too large and the procedure to computationally intensive to model enough networks to cover the range of what is possible. Furthermore, a minimum spanning tree (MST) will be used as a starting point, which is the minimum number of connections needed to fully connect all nodes, in order to avoid problems of calculating current path lengths when nodes are not part of the same component. From the minimum spanning tree, the efficiency improvement will be calculated for each unconnected pair of nodes by dividing current path length over the then-present network by the path length of a direct link between the pair, both defined using the temporal distances between places that are derived from least-cost path reconstructions. A number of links that provide the greatest efficiency improvement can then be iteratively added to the network, recalculating the efficiency improvements after each addition due to potential changes in current path lengths. This study will evaluate efficiency networks after the increase of the total number of links by 10%, 25%, and 50% with respect to the minimum spanning tree, as well as the minimum spanning tree itself for reference purposes.

6.2.4 Comparative methodology

The goal of this study is to compare the various network construction techniques and evaluate which one of them achieves the best representation of a potential local transport system that connects the rural settlements to the *castella*, with the purpose of supplying the military population primarily with agrarian surplus products. This is not to say that each connection in one of the modelled networks is equally likely to be travelled: the actual flow of goods over the network is dependent on the supply of the rural population and demand of the military population, which is difficult to quantify and outside the scope of this study. The routes that are modelled through these network construction techniques, whether they are based on some sort of agency, such as the maximum distance, proximal point or efficiency networks, or not, such as the Delaunay triangulation and Gabriel graph, should still be seen as potential routes for transport rather than lines of flow that are constantly travelled. The essential question that is approached is thus not how provisioning occurred precisely, nor does this approach intend to imply that other sites such as the *civitas* capitals did not play a role, but the question is rather which network can best be used to approximate the potential routes of transport. The results in turn may be used for more quantitative studies at a later stage, including the question how goods flowed from the rural population to the military population (section 6.4.3).

The networks can thus be tested on at least the following properties: 1) all *castella* must be part of the connected network or at least a sufficiently large component of it; and 2) the *castella* must be relatively efficiently accessible for provisioning to take place. The latter property can be evaluated using average path length, a network metric that calculates the average distance to get to a node from all other nodes in the network, and in this case our primary interest is of course in the average path length to get to the *castella* from the rural settlements, rather than the average path length for the entire dataset. Average path length can be weighted, making it possible to take the temporal distances in the network into account. Unfortunately this only allows for a fair comparison if all nodes in the network are connected, as the value clearly changes when more peripheral nodes are not part of the component for which average path lengths are calculated. Considering this from an archaeological perspective however, it is very unlikely that goods will be moved from a rural settlement on one side of the region to a *castellum* on the other side of the region, yet average path length does take into account this possibility. It is therefore valuable to also calculate the 'local' average path length, which is defined here as the average distance to get to a node from a limited n of the most proximal nodes. This has the advantage of being a more realistic evaluation from an archaeological point of view, as well as removing the condition that all nodes in the network should be connected: a *castellum* now only needs to be in a component of minimum size of $n + 1$. Without information on military demand and rural supply capabilities, it is unknown how many rural settlements are actually needed to support a Roman *castellum*, and demand and supply patterns may be heterogeneous across the region as well. To keep matters simple here, the 'local' average path length will be calculated for a n of 25, which is roughly equal to 5% of the total number of settlements considered in this study. Furthermore, competition between *castella* will not be included, meaning that a settlement can appear among the most proximal nodes to more than one *castellum*.

There are also some other aspects that can be considered as complimentary criteria to evaluate how well the modelled networks represent local transport networks. Firstly, there is simply the number of links and the related network metric of average degree, which is the average number of neighbours per node. A number of links or an average degree that is very high can most likely be considered unrealistic, since the networks are supposed to represent movement though the landscape and it is very unlikely that one would be able to move to a very large number of other places without going through any place on the way there. Secondly and similarly, very long links cross-cutting the network should not be expected, as it is unlikely that such a path would be possible without passing through another place. Other network metrics are more difficult to relate to how well a network performs as a representation of local transport networks, but can say something about the structure of the networks themselves. Examples are the average clustering coefficient, which is an average of the measures of the extent to which the neighbours of a node are also neighbours of each other, and network heterogeneity, which is a measure of the tendency of the network to contain a few highly connected hub nodes among a large number of less well-connected nodes.

6.2.5 Results

Examples of the constructed networks are shown as straight line representations in Figures 6.11-15, with images of all constructed networks available in Appendix 4. The straight lines in the network are actually a simplified representation of the least-cost paths, which are of course not necessarily straight, and the associated temporal distances that were either used in the construction of the networks or assigned to the links afterwards (in the case of the Delaunay triangulation).

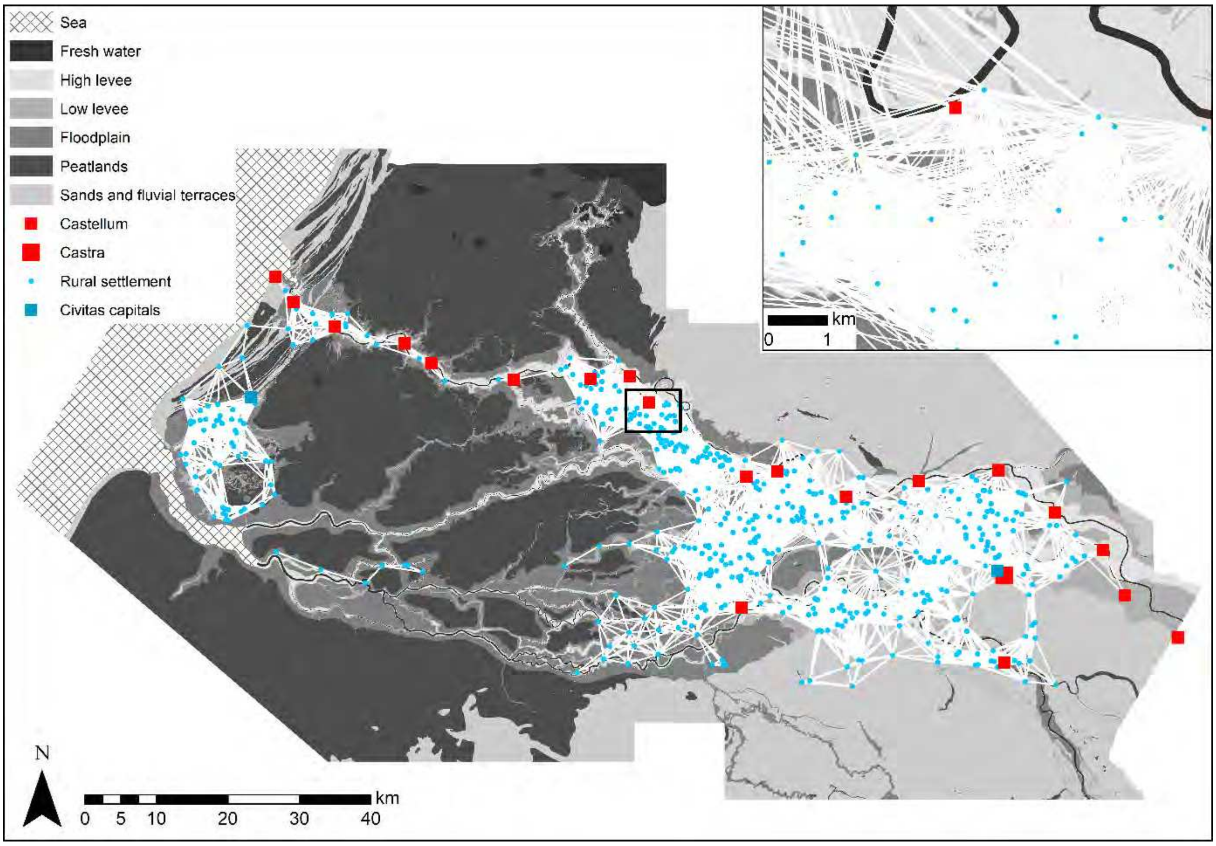


Figure 6.11. Maximum distance network with D=120 min. The inset shows a detail of the central part of the study area.

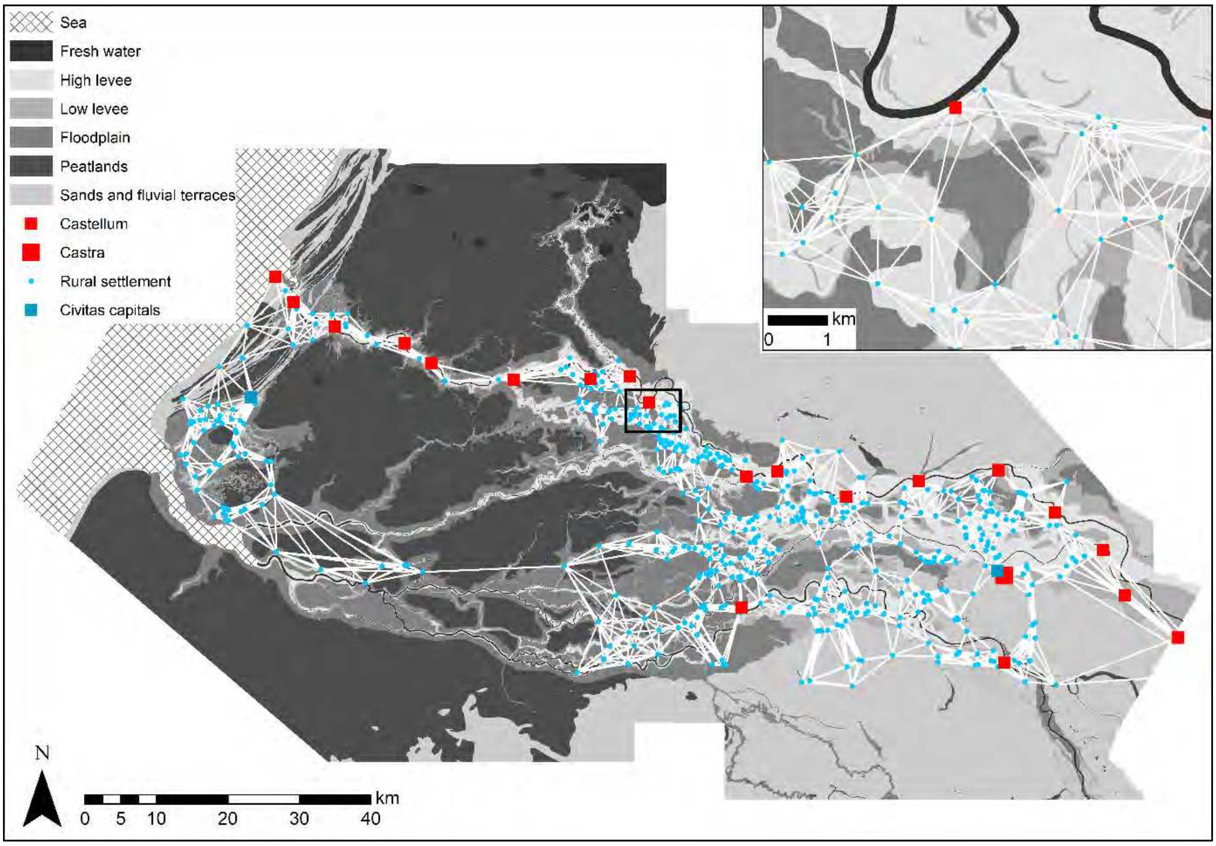


Figure 6.12. Proximal point network with k=7.

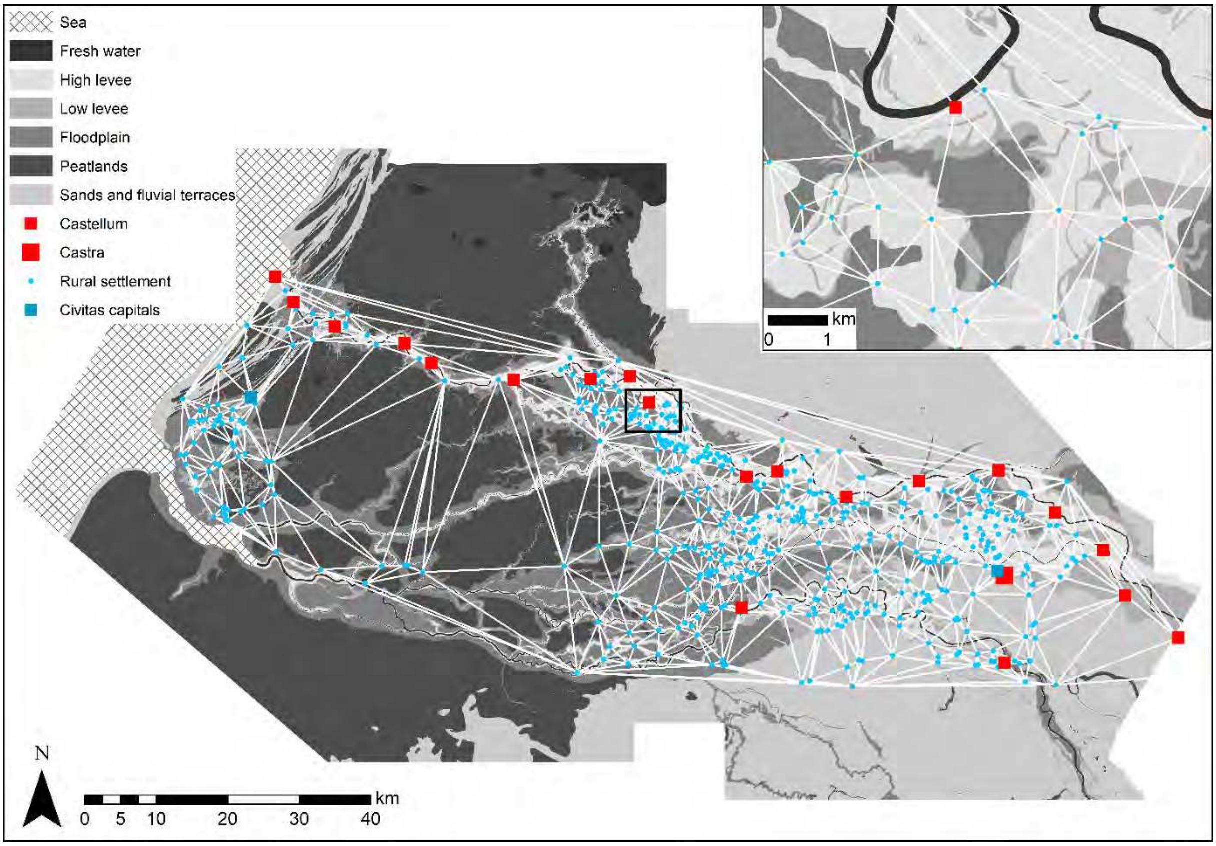


Figure 6.13. Delaunay triangulation.

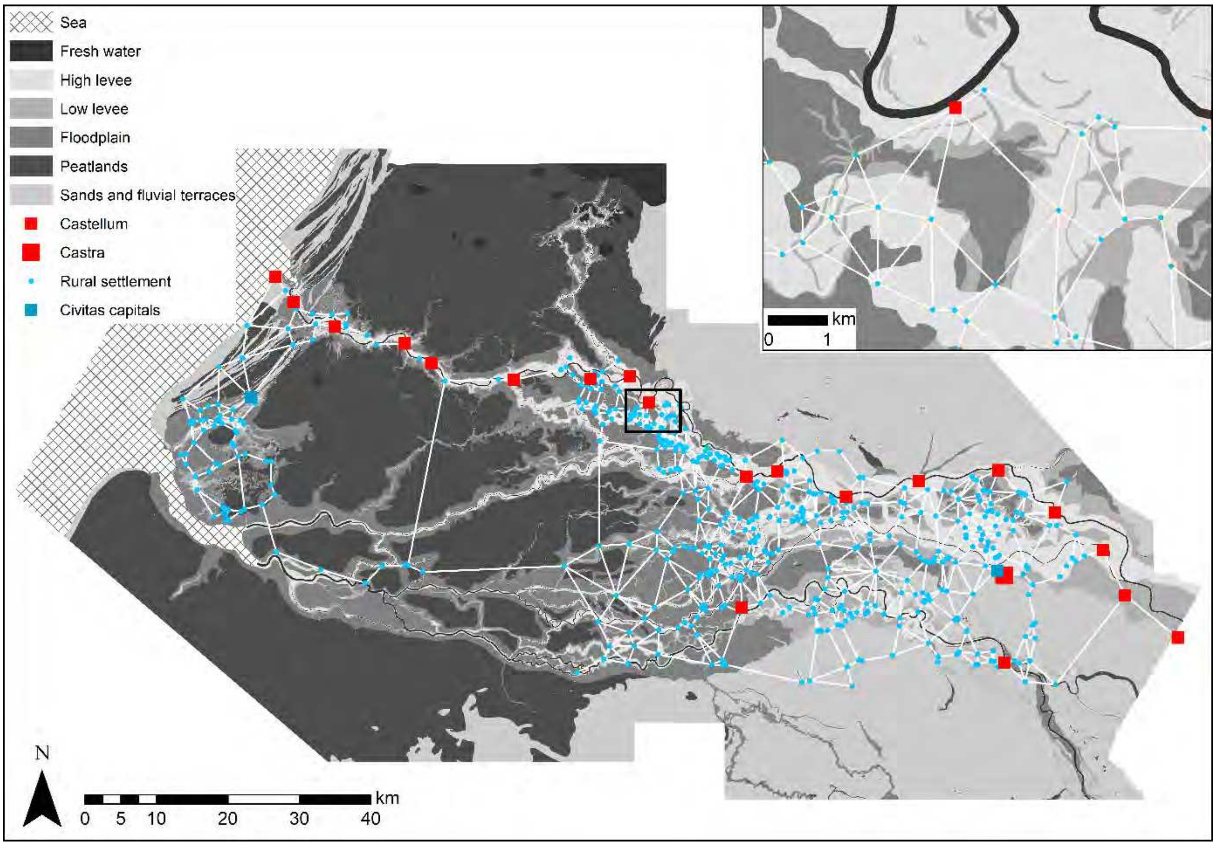


Figure 6.14. Gabriel graph based on the temporal distances between sites.

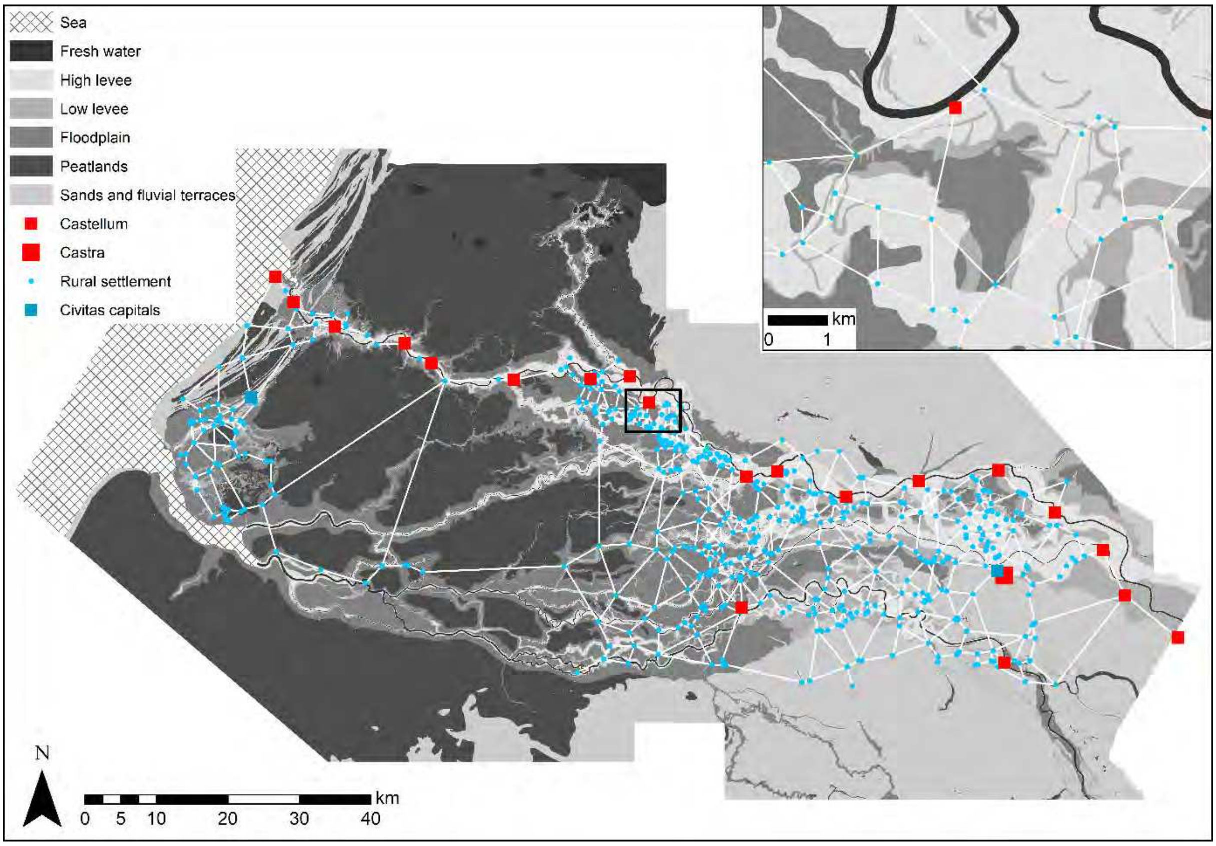


Figure 6.15. Efficiency network with a 50% increase of links with respect to the minimum spanning tree.

	Number of nodes	Number of links	Connected components	Isolated nodes	Average degree	Average clustering coefficient	Network heterogeneity
MD (30 min)	524	918	143	83	3.504	0.467	0.856
MD (60 min)	524	2813	36	21	10.737	0.644	0.713
MD (90 min)	524	5528	14	6	21.099	0.674	0.597
MD (120 min)	524	8643	5	2	32.989	0.708	0.528
PP (3)	524	1013	13	0	3.866	0.59	0.242
PP (5)	524	1665	1	0	6.355	0.606	0.205
PP (7)	524	2307	1	0	8.805	0.626	0.184
Delaunay	524	1557	1	0	5.943	0.45	0.261
Gabriel	524	910	1	0	3.473	0.216	0.331
MST	524	523	1	0	1.996	0	0.328
Efficiency (10%)	524	575	1	0	2.195	0	0.28
Efficiency (25%)	524	654	1	0	2.496	0.004	0.261
Efficiency (50%)	524	785	1	0	2.996	0.051	0.289

Table 6.1. General network characteristics of the investigated network construction techniques.

Table 6.1 presents the general network characteristics of the investigated network construction methodologies, namely maximum distance (MD) networks with a number of different thresholds, proximal point (PP) networks with a varying number of nearest neighbours, the Delaunay triangulation, the Gabriel graph, the minimum spanning tree (MST), and efficiency networks with a varying percentage of links added with respect to the minimum spanning tree.

One of the most obvious differences between the various networks is the number of links present in the network. Especially the maximum distance networks, by virtue of not having any limitations on the number of neighbours a node can connect to, have a disproportionally large amount of links. This is also reflected in the related property of average degree. The minimum spanning tree and the efficiency networks, which are constructed using the minimum spanning tree as a basis, have a relatively low number of links and average degree. What is also noteworthy and important for further network comparisons, is that the maximum distance networks and the proximal point network with a k of 3 are not entirely connected, influencing metrics that are calculated on the network as a whole.

The average clustering coefficient is highest for the maximum distance networks, which is to be expected based on the unlimited amount of neighbours a node can have. Proximal point networks also have a relatively high clustering coefficient, showing that two nodes that are proximal to a third node are also quite likely to be proximal to each other. The average clustering coefficient for the Delaunay triangulation is quite predictable, as the division of the dataset into triangles creates a predictable amount of neighbours that are also neighbours to each other. It varies almost only based on the proportion of nodes that are on the convex hull and the nodes within the hull that only have three neighbours (i.e. a node being contained in a greater triangle), meaning that for sufficiently large Delaunay triangulations it will approximate the same value (Taylor and Vaisman 2006, 041925–4). In contrast, the average clustering coefficient of the Gabriel graph is fairly low, as neighbouring nodes can only be connected in a triangle when none of the angles of the triangle as well as those of the opposite nodes of neighbouring triangles are equal to or greater than 90°. The minimum spanning tree has an expected average clustering coefficient of 0, and this doesn't increase greatly through the addition of links in the efficiency networks. This is also conforming to expectations as the algorithm firstly connects nodes that are not easily reached over the existing network, meaning that node pairs that already share a single neighbour are relatively unlikely to be connected.

In terms of network heterogeneity the maximum distance networks again provide the highest values, indicating those networks have a few nodes that are very highly connected, and many nodes that are relatively poorly connected. The so-called hub nodes are likely centrally located in areas of high site density, whereas the poorly connected nodes are the more peripheral sites and sites in areas of lower site density. The other networks have a much lower network heterogeneity and are all in a similar range (0.2-0.33). The difference between hub nodes and more poorly connected nodes is much smaller for these networks, which can be related to the fact that all these networks have some property that limits the amount of neighbours a node can have.

Table 6.2 presents the average path length (APL) in minutes to reach the *castella* from all other sites in the analysed networks. The maximum distance networks and the proximal point network with a k of 3 were shown to be not completely connected, making it unfair to compare APL to the networks that are. For this reason, the relevant cells in the table are given a grey colour. For the completely connected networks, the overall average APL to reach the 16 *castella* is given at the bottom of the table. The subsequent relative performance is defined as how much lower or higher that value is for a particular network (nw) compared to the overall average APL of the set of all completely connected networks (NW), which is given in the final column and calculated as Equation 6.1.

	MD (30 min)	MD (60 min)	MD (90 min)	MD (120 min)	PP (3)	PP (5)	PP (7)	Delaunay	Gabriel	MST	Efficiency (10%)	Efficiency (25%)	Efficiency (50%)	Average
Katwijk-Brittenburg	*0.0*	*162.3*	*220.9*	*451.2*	*464.6*	1384.1	1307.5	1260.6	1379.8	2078.3	1489.5	1427.6	1381.7	
Valkenburg	*8.0*	*103.5*	*159.4*	*384.3*	*91.1*	1326.7	1246.2	1195.7	1313.8	2008.5	1419.7	1357.8	1316.4	
Leiden-Roomburg	*0.2*	*88.2*	*119.5*	*399.5*	*1009.1*	1238.5	1150.6	1100.2	1211.7	1876.9	1319.4	1256.0	1213.9	
Alphen aan den Rijn	*0.8*	*57.5*	*181.9*	*535.2*	*97.4*	1111.3	1038.9	967.5	1078.4	1747.8	1189.7	1122.3	1078.6	
Zwammerdam	*10.4*	*40.2*	*237.2*	*602.1*	*61.6*	1055.2	982.6	912.7	1019.2	1690.6	1131.9	1063.0	1014.8	
Woerden	*0.0*	*18.0*	*18.0*	*809.1*	*646.5*	917.3	846.2	771.5	879.9	1552.6	990.2	923.4	871.7	
Vleuten-De Meern	*23.5*	*515.7*	*620.5*	*617.0*	*934.2*	823.1	720.1	686.4	745.1	1462.6	848.2	787.0	732.7	
Utrecht	*0.7*	*494.9*	*572.0*	*568.9*	*434.1*	905.3	687.2	654.4	734.0	1530.0	848.0	784.5	708.2	
Vechten	*126.8*	*412.1*	*503.2*	*502.2*	*190.5*	718.0	642.2	604.7	664.5	1355.9	771.5	714.0	659.1	
Rijswijk	*26.4*	*344.1*	*357.2*	*354.0*	*789.4*	627.6	551.6	519.1	557.1	1136.1	665.2	599.6	559.9	
Maurik	*193.1*	*344.9*	*353.7*	*355.1*	*706.8*	618.1	545.2	527.9	576.9	1113.7	651.6	600.5	578.1	
Kesteren	*183.8*	*431.8*	*354.5*	*355.5*	*603.3*	653.5	573.0	556.6	603.0	1255.9	680.1	646.9	615.5	
Randwijk	*13.0*	*202.0*	*431.5*	*432.1*	*535.1*	821.2	673.4	648.6	701.8	1680.4	773.5	734.6	709.6	
Arnhem-Meinerswijk	*0.0*	*197.9*	*547.0*	*547.0*	*630.4*	949.7	793.0	771.7	826.0	2115.5	938.4	880.7	844.9	
Loowaard	*23.3*	*103.5*	*620.9*	*616.5*	*550.3*	1014.1	876.3	858.0	904.7	2352.4	1037.5	1000.3	934.2	
Herwen-De Bijland	*0.0*	*94.8*	*719.9*	*715.3*	*670.6*	1122.0	974.2	962.9	1035.4	2265.8	1126.6	1089.0	1048.1	
Overall average						955.4	850.5	812.4	889.5	1701.4	992.6	936.7	891.7	991.3
Relative performance						3.6%	14.2%	18.0%	10.3%	-71.6%	-0.1%	5.5%	10.0%	0.0%

Table 6.2. Average path length (in minutes) of the castella in the investigated networks. Values in italics indicate sites that cannot be reached by all other sites in the network.

	MD (30 min)	MD (60 min)	MD (90 min)	MD (120 min)	PP (3)	PP (5)	PP (7)	Delaunay	Gabriel	MST	Efficiency (10%)	Efficiency (25%)	Efficiency (50%)	Average
Katwijk-Brittenburg	*0.0*	*171.8*	*230.5*	225.2	235.3	203.9	199.5	203.8	211.7	286.2	230.9	230.9	212.7	
Valkenburg	*12.0*	*109.6*	*166.3*	160.9	170.6	164.3	151.8	152.0	160.2	221.4	166.0	166.0	165.4	
Leiden-Roomburg	*0.4*	*93.4*	*124.7*	129.0	147.4	138.5	127.1	133.6	139.3	152.9	149.1	149.1	141.0	
Alphen aan den Rijn	*1.6*	*69.0*	*189.8*	201.3	201.5	196.6	189.9	190.6	203.6	212.2	205.5	205.5	203.6	
Zwammerdam	*15.6*	*48.2*	*247.5*	257.3	235.3	232.9	223.7	228.0	238.4	241.9	238.9	238.9	238.4	
Woerden	*0.0*	*36.0*	*36.0*	196.4	206.7	187.5	184.7	179.9	204.7	213.5	213.5	209.1	206.5	
Vleuten-De Meern	*25.5*	49.7	48.2	48.2	112.3	51.8	51.4	51.5	55.1	75.9	69.9	60.5	55.3	
Utrecht	*1.4*	85.0	75.6	75.3	164.6	105.1	78.9	79.9	89.3	123.2	104.9	96.3	91.2	
Vechten	58.2	48.2	48.0	48.0	55.2	50.5	49.2	50.4	51.6	123.7	64.8	64.2	55.2	
Rijswijk	*31.7*	70.0	67.3	66.9	*101.7*	74.3	71.2	71.3	73.4	86.5	86.5	78.9	74.3	
Maurik	112.0	68.3	64.7	64.6	103.5	71.7	68.7	67.4	76.6	91.1	82.5	79.7	79.7	
Kesteren	80.7	65.2	59.3	59.3	69.1	63.6	62.3	62.4	67.1	89.1	82.2	79.4	74.0	
Randwijk	*26.0*	120.9	110.8	107.6	137.7	118.7	114.2	111.7	117.1	158.8	137.8	121.6	120.1	
Arnhem-Meinerswijk	*0.0*	109.8	91.8	90.0	*70.4*	110.3	92.8	93.5	98.2	169.7	122.1	114.4	112.9	
Loowaard	*34.9*	*115.0*	103.9	101.9	464.7	105.2	104.3	104.1	109.2	267.3	150.7	150.2	126.7	
Herwen-De Bijland	*0.0*	*105.4*	165.1	159.8	439.8	166.8	160.6	159.6	184.0	207.5	190.6	190.6	187.7	
Overall average				124.5		127.6	120.7	121.2	130.0	170.1	143.5	139.7	134.0	134.3
Relative performance				7.3%		5.0%	10.1%	9.7%	3.2%	-26.7%	-6.9%	-4.1%	0.2%	0.0%

Table 6.3. 'Local' average path length (in minutes) of the castella *from the 25 most proximal nodes in the investigated networks. Values in italics indicate sites that cannot be reached by at least 25 other sites in the network.*

$$relative\ performance_{nw \in NW} = 1 - \frac{overall\ average\ APL_{nw}}{\langle overall\ average\ APL_{NW} \rangle} \tag{6.1}$$

Table 6.3 presents the 'local' APL in minutes to reach the *castella* from the 25 sites that are most proximal to each *castellum* in terms of time. This has the advantage of being able to compare individual *castella* across networks as well as entire networks to each other even when they are not fully connected. A number of cells still hold invalid values, because these *castella* are not in a component of a size 26. The maximum distance network with a D of 120 minutes can now validly be compared in its entirety in addition to the ones that were already completely connected. The overall average 'local' APL and the relative performance of these networks are again presented in the bottom rows.

6.2.6 Discussion

Before evaluating each network construction technique on how well it achieves the desired goal of representing potential local transport networks, it is important to shed some more light on the character of the results through a general evaluation, which will be detailed in the following subsections.

6.2.6.1 General evaluation: least-cost path modelling

Networks have been constructed on the basis of a dataset of least-cost paths, which has some implications for the general applicability of the methodology of comparing network construction techniques outlined in this study, as well as the uncertainty within the results stemming from these least-cost paths.

Firstly, it must be noted that the comparisons made between these networks assumes isotropic costs: the travel time between any pair of nodes is independent of the direction of travel. When this methodology would be applied to anisotropic datasets, for instance when slope would be a factor, some changes will occur that likely influence the results. Primarily, paths in the networks will become directional, and it is not certain that a connection between two sites can be travelled in both directions. In an extreme example of a proximal point network, a *castellum* may become unreachable if it is not the nearest neighbour to another site. In short, the best network construction technique to represent a potential network of local transport found using this methodology is thus dependent on travel being isotropic, and may be different in circumstances of anisotropic costs.

As with many computational approaches in archaeology, there is always a degree of uncertainty in the results that can be caused by a number of sources. In least-cost path modelling (see also section 5.3.3) that uncertainty can be the result the chosen software for calculating the paths (Gietl *et al.* 2008), the site dataset from which the source and destination of the LCP are derived (see section 3.4.2 and Verhagen *et al.* 2016b for (chronological) uncertainty in the site dataset), the chosen method and parameters for calculating the costs of movement (Herzog 2013d), as well as uncertainties in the palaeogeography that forms the basis for establishing those costs (see section 2.4). Most of these have been covered to some extent in aforementioned sections and references, but particular to this case study is the last one: the reconstructed palaeogeographic map. In the Rhine-Meuse delta the largest sources of uncertainty for reconstructing this map are post-Roman fluvial erosion, peat extraction and modern urban developments. The results from section 5.3.3 show that this can indeed have an impact on the precise route a least-cost path takes, but the extent to which this happens is very dependent on the local geography and thus not easily predictable. However, the areas where such uncertainty is large are relatively small compared to the areas where the reconstruction is more reliable. The effect on the complete dataset of least-cost paths is thus also relatively minor: it could certainly change networks locally, but will not change the picture of a network as whole.

6.2.6.2 General evaluation: generality of the results

The costs used in our model are expressed in terms of time and are calculated using a formula for walking by Pandolf *et al.* (1977). For this case study, the weight, load and metabolic rate parameters have been fixed to study only a transport network for walking while carrying a load of 20 kg, resulting in a direct relation between the terrain coefficient η and velocity V (Eq. 6.2).

$$V = C\eta^{\frac{1}{2}} \text{ with } C \approx 1.32 \tag{6.1}$$

Of course the constant C in this formula changes when one of the parameters is altered, for instance when modelling walking while carrying a different load, which has also been carried out (Groenhuijzen and Verhagen 2015; section 5.2.1) but is left outside the scope of this particular study. Nevertheless, it can be deduced that knowledge of the exact travel times (based on V) is generally not necessary to draw the comparisons on the studied network construction techniques in this study. In fact, changing one parameter, such as carried load, only changes C and thus scales V evenly, so that the distances between sites in relation to each other remain the same. As a consequence, the proximal point and efficiency networks as well as the Delaunay triangulation and Gabriel graph would remain in the same configuration regardless of the other parameters, and any results and conclusions drawn from these particular parameter settings thus have greater generality for any other parameter choices, such as changing the carried load. Only for the maximum distance network it is a bit different, but it still scales evenly, so that any changes are proportional (e.g. a doubling of C would replace the network configuration of $D = 120$ minutes by that of $D = 60$ minutes). While it may thus be argued that it is altogether unnecessary to know V to construct networks out of least-cost paths and compare them to each other, since knowing η is enough, this would have the downside of producing a less tangible output in the form of distances being expressed in units of landscape resistance rather than units of time. In order to maintain comprehensibility the choice was made to retain the results of the least-cost paths in terms of time and thus only study the network of walking under the aforementioned fixed parameter choices, although it must be kept in mind that for the current study this is an unnecessary distinction and the comparisons made have greater generality.

This cannot be said for modes of transport outside the modes of walking covered by the formula of Pandolf *et al.* (1977), such as ox-cart and mule-cart transport (see section 5.2.2). The reason for this is that η is not a universal terrain coefficient for movement but is specified for walking. Without going into too much detail, the movement of animal-drawn carts is slightly more difficult to model as friction is not only dependent on the nature of the contact surface (the wheel on the terrain) but also on axle friction and on whether or not the vehicle is already moving (Raepsaet 2002, 22–24). The results of the comparison of network construction techniques made in the case study of this study are thus not directly translatable to networks of transport with animal-drawn carts, although the methodology itself is of course repeatable.

6.2.6.3 *General evaluation: temporal distances versus geodesic distances*

Regarding the use of temporal distances rather than geodesic distances for constructing networks, it may be relevant to see whether this actually makes a difference for the results drawn in the previous section. We can compare the results of the analysis for instance to a null model, the null model in this case being established on the basis of setting the terrain coefficient η to a constant 1, so that the V equals 5 km/h and the costs for calculating the LCPs are thus always approximately 69 s per 50 m, effectively resulting in geodesic paths with a distance expressed in time. The configuration of the networks (in terms of links present or absent) resulting from the null models is not the exact same as their temporal counterparts, the exception being the Delaunay triangulation which was already constructed on the basis of geodesic distances. This is most noticeable in the maximum distance networks with a D of 90 and 120 minutes, the former under $\eta = 1$ becoming connected enough to measure the overall average 'local' APL (i.e. all *castella* in components of a size > 25), whereas the latter even becomes fully connected (i.e. no more isolated nodes).

	Overall average APL			**Overall average 'local' APL**		
	Temporal	**Null**	**Difference**	**Temporal**	**Null**	**Difference**
MD (30 min)						
MD (60 min)						
MD (90 min)					85.4	
MD (120 min)		582.2		124.5	84.2	+44.0% ±12.4%
PP (3)						
PP (5)	955.4	691.5	+37.6% ±8.2%	127.6	92.8	+36.9% ±13.9%
PP (7)	850.5	610.4	+38.9% ±3.4%	120.7	87.0	+37.5% ±6.2%
Delaunay	812.4	582.1	+39.4% ±1.5%	121.2	86.7	+39.0% ±6.4%
Gabriel	889.5	644.1	+38.1% ±2.3%	130.0	94.1	+37.6% ±7.3%
MST	1701.4	1166.4	+46.0% ±3.0%	170.1	123.5	+36.6% ±5.4%
Efficiency (10%)	992.6	737.7	+34.7% ±2.8%	143.5	107.6	+33.4% ±6.1%
Efficiency (25%)	936.7	676.8	+38.5% ±2.5%	139.7	101.9	+38.1% ±7.1%
Efficiency (50%)	891.7	648.7	+37.6% ±1.4%	134.0	97.1	+38.1% ±5.7%

Table 6.4. The overall average APL *and 'local'* APL *(in minutes) of the 16* castella *in the investigated networks, compared between the original model based on temporal distances with a variable terrain coefficient* η *and a null model where* η*=1.*

Table 6.4 shows a comparison between the measurements of the overall average APL and 'local' APL of the original networks modelled using the temporal distances between sites over a palaeogeographic map with a varying η and the null model where $\eta = 1$. The variation in difference of the temporal models with the null models is not large, since the original measurements are on average all between 37% and 39% greater than those of the null model, exceptions being the maximum distance network, the minimum spanning tree and the smallest efficiency network. However, the variation in difference is large enough to have an effect on the results drawn in the previous section, particularly for the 'local' APL: if the null model (essentially a geodesic model) was used instead of the temporal one, the lowest overall average 'local' APL would have been achieved by the maximum distance network with $D = 120$ minutes, followed by the Delaunay triangulation, whereas the temporal model favoured the proximal point network with $k = 7$. On an individual level the differences are even greater: the *castellum* of Maurik for example has an average 'local' APL in the temporal proximal point network with $k = 5$ that is only

7.6% greater than the equivalent null model, while the same measurement for the maximum distance network with $D = 30$ minutes is 105.9% greater than the null model. The conclusion that can be drawn from this is that making use of temporal distances between sites instead of a simple geographic/geodesic model thus has a noticeable impact on the modelled networks (unlike e.g. the primarily water-based network of Rivers *et al.* (2013)), and thus may affect any results and conclusions that we may draw from them.

6.2.6.4 General evaluation: combining network principles

Each of the studied networks have a certain set of principles that govern why a path should or should not be part of the network. For example, the maximum distance network assumes a certain limitation on the length one could move without passing through a known waypoint and the proximal point network assumes a limit to the amount of neighbours one can reach from a site. The Delaunay triangulation and Gabriel graph build paths based on geometric properties, and paths not included might be deemed 'unnecessary' to navigate the network, at least from the geometric perspective. It is possible (and arguably likely) that a more accurate network of transport is actually based on multiple of these principles. An interesting question would thus be if a combination of network techniques would yield fundamentally different networks than the ones already studied.

For this exercise, a combination was made of the Delaunay triangulation with the maximum distance ($D = 120$ minutes) and proximal point networks ($k = 5$ and $k = 7$). In other words, the maximum distance and proximal point networks were filtered to include only those paths that are also part of the Delaunay triangulation. For the filtered maximum distance network the average APL and 'local' average APL to the *castella* are on average 4.2% and 4.0% greater than the original. For the proximal point network with $k = 5$ this is 1.7%/1.6%, and with $k = 7$ this is 3.6%/3.5%. The greatest deviation is the *castellum* of Utrecht with a 'local' average APL that is 11.1% greater in the filtered proximal point network with $k = 7$. It indicates that a noticeable number of paths in the network towards this *castellum* are not part of the Delaunay triangulation, but this observation is a relative outlier and does not hold for the majority of *castella*. Generally speaking, the difference between the maximum distance and proximal point networks filtered for the Delaunay triangulation and their original counterparts is fairly small, certainly compared to the difference of 37%-39% observed between the original temporal models and the null models, described in the previous section.

6.2.6.5 General evaluation: APL dependency on number of links

Given the wide variation in number of links per network, it may be possible that decreases in the overall average APL are the result of increases in the link count. Figure 6.16 shows that there is not a clear linear relation between the two variables, which is also revealed by a Pearson correlation coefficient (PCC) of $r = -0.44$. The distribution of the data points may suggest an inverse exponential relation to be more likely than a linear one, but the logarithm of the overall average APL against the number of links only results in a slight increase to $r = -0.48$. It is a different story for the overall average 'local' APL however (Fig. 6.17). A possible linear relation between the number of links and the overall average 'local' APL gives $r = -0.39$, but this is heavily influenced by the maximum distance network with $D = 120$ minutes. When this is excluded as an outlier, the PCC arrives at $r = -0.72$. Doing the same for the number of links against the logarithm of the overall average 'local' APL even gives $r = -0.75$, revealing a relatively strong inverse exponential correlation.

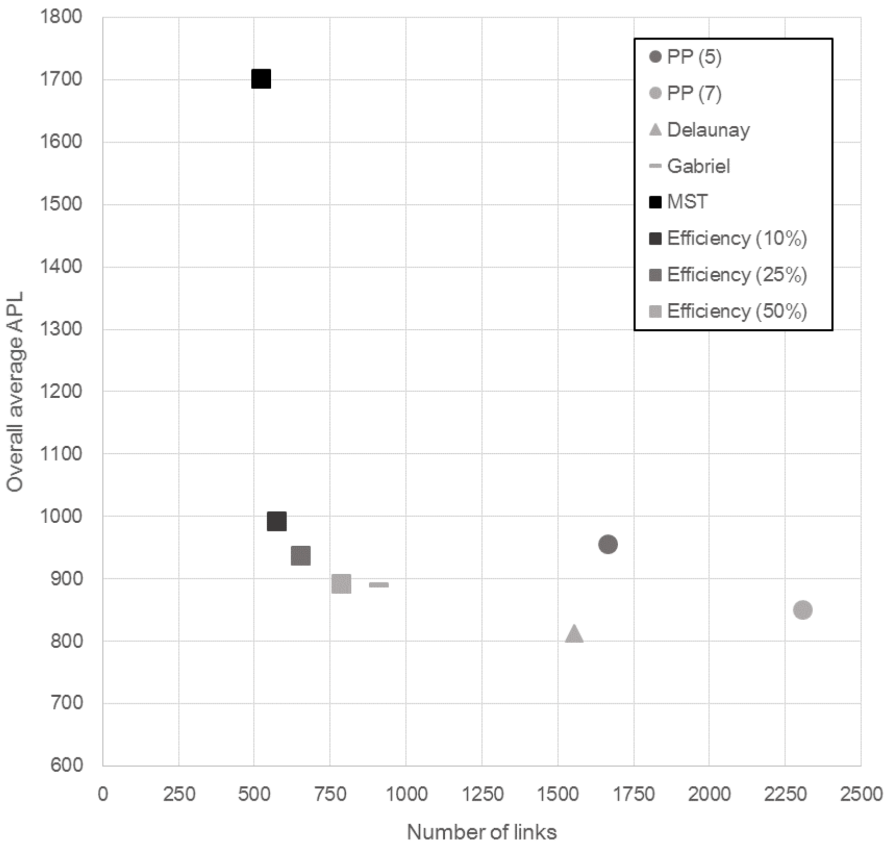


Figure 6.16. Number of links plotted against overall average APL.

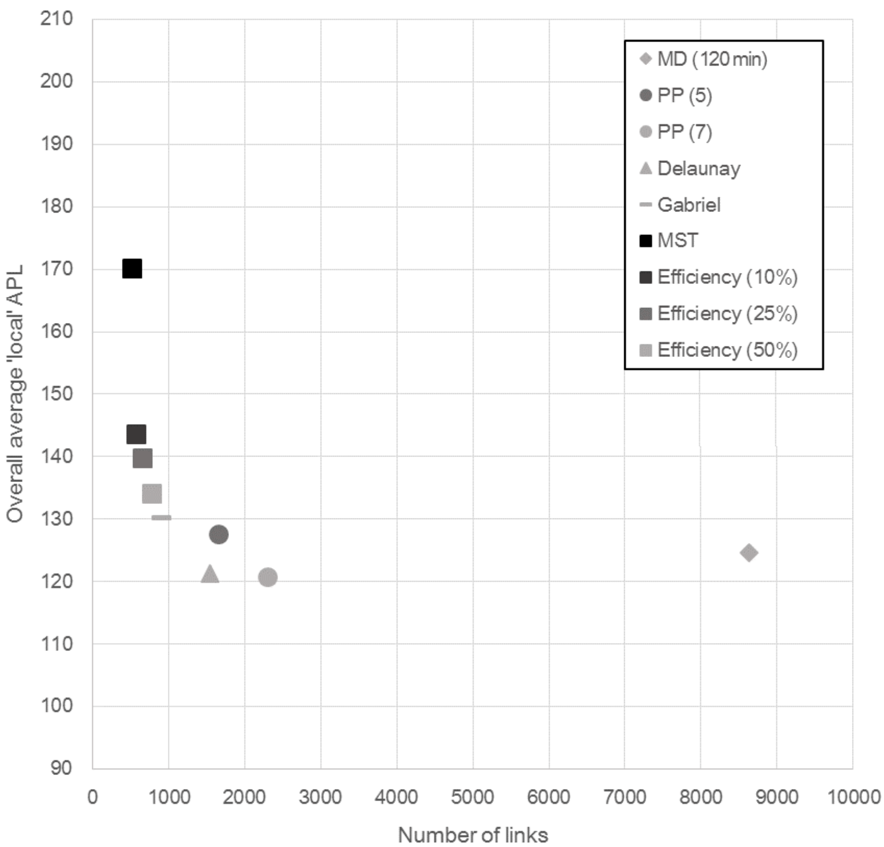


Figure 6.17. Number of links plotted against overall average 'local' APL.

A strong correlation between the number of links and lower APL of course does not invalidate any comparisons between the networks. Since the number of links in a network is an inherent result of the network construction technique used, it is an equally valid part of the comparison. Furthermore, a good linear correlation provides an extra option for comparisons, as it may be useful to see which networks most positively (or negatively) deviate from what would be expected if one would assume a causal relationship between the number of links and lower APL. The linear regression line of the logarithm of the overall average 'local' APL against the number of links is drawn in Figure 6.18. The network that is furthest below this line and thus performs better on this metric is the Gabriel graph based on temporal distances, followed by the Delaunay triangulation and the efficiency network with 50% link increase. In contrast, the proximal point networks are actually above the linear regression line and perform slightly worse than one would predict when assuming an inverse exponential relation between the two variables.

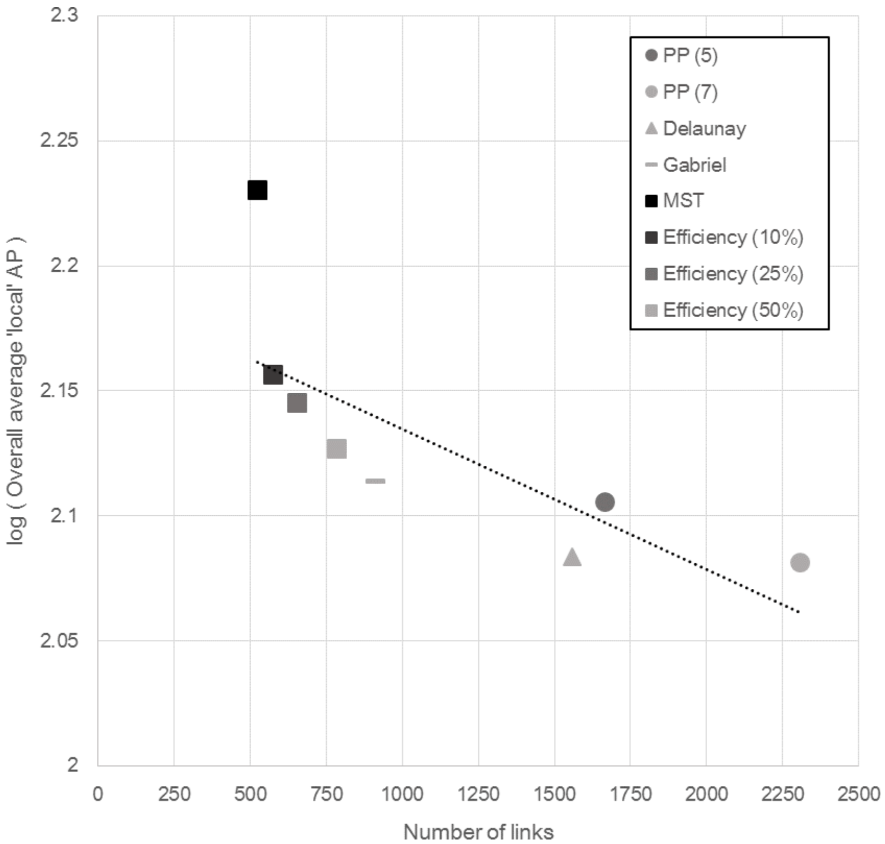


Figure 6.18. Logarithm of the overall average 'local' APL plotted against the number of links, with the linear regression line drawn.

6.2.6.6 Maximum distance networks

The first network construction technique to be evaluated here based on the criteria established in section 6.2.4 is the maximum distance network. Almost immediately this provided a problem, as the method failed to fully connect all nodes in the network even for the highest values of D, and thus could not be evaluated on the average path length to reach the Roman *castella* over the entire network. When only considering the 25 most proximal nodes to a *castellum*, some proved to be in a component large enough to be evaluated, but only for a D of 120 minutes this became the case for all *castella*. At the same time, the number of links and the related property of average degree increased greatly. This can be considered an unrealistic representation of a transport network, as it is very unlikely that one would be able to move to so many places without going through another place on the way there. Furthermore, the increase in the number of links did not result in a notable decrease in the 'local' APL to the *castella*, to the point that it had to be excluded as an unrealistic outlier when investigating a correlation between the two variables. A question that remains is then why a maximum distance network worked quite well in our earlier case study (Groenhuijzen and Verhagen 2015). The underlying reason for this is the specific situation of the case study. The area was chosen as it was relatively well understood and thoroughly investigated in archaeology, and it has a relatively high site density. The four *castella* that were included in that case study (Vleuten-De Meern, Utrecht, Vechten and Rijswijk) can all be reached by at least 25 other sites in maximum distance networks with a D of 60 minutes, and one even with a D of 30 minutes. This relatively low cut-off point results in an average degree that is not yet unreasonably high while at the same time creating a high network heterogeneity, which more easily reveals central nodes and bottlenecks in the network. The conclusion that can be drawn from this is thus that maximum distance networks can work well for local case studies that are relatively well understood, but don't work on the scale of the entire region where there are large variations in site density.

6.2.6.7 Proximal point networks

Proximal point networks have the potential to function somewhat better as they have a built-in limitation on the number of neighbours a node can have in the network. However, the network is not completely connected for a k of 3. For higher values the number of links and average degree already increase to values that are slightly on the high side compared to the following networks, yet are not entirely unrealistic. In terms of APL to the *castella* the proximal point networks for a k of 5 and 7 perform quite well, and the network for a k of 7 even has the lowest overall average 'local' APL. However, when considering its deviation from the regression line of that variable with the number of links, it actually doesn't seem to reach the values that could be expected with such a high link number. Summarising, proximal point networks for a lower k are probably not a good representation of a local transport network to connect the rural settlements to the *castella*, due to not being connected enough. Proximal point networks for a higher k perform quite well on the indicators of APL and 'local' APL, but the average degree is just on the high side.

6.2.6.8 Delaunay triangulation

The Delaunay triangulation has an advantage over other network construction techniques by being completely connected by default. However, a clear disadvantage in its construction is that it does not take into account the temporal distances between places that are derived from the least-cost path reconstructions, only being able to assign those values to the links in the network afterwards. Nonetheless, the Delaunay triangulation performs best in terms of overall average APL and second-best on the 'local' APL, and furthermore has a reasonable average degree. However, the network structure itself raises some questions, such as the very long links along the edges of the network and the long links cross-cutting the relatively inaccessible floodplains and peatlands in the west and centre of the research area. While the temporal distances assigned to these links are relatively long, making them unlikely (but not entirely avoidable) to be taken into account when calculating the 'local' APL, it would be a more realistic representation and simply tidier if these links would not be present in the network to begin with. The Delaunay triangulation as a network construction technique can thus be stated to appear as a very good candidate for a representation of a local transport network directed at the *castella* based on its relative good performance on the evaluated metrics, but some concerns on the inclusion of unrealistic links in the network are warranted.

6.2.6.9 *Gabriel graph*

A possible alternative to the downsides of the Delaunay triangulation is a Gabriel graph, which in Euclidian space is a subgraph of the Delaunay triangulation, retaining the complete connectedness but without many of the unrealistically long links in the network. Moreover, its relatively simple principles also allow for the construction of a Gabriel graph using the temporal distances between places, rather than just the geodesic distances. The downside of losing a number of links is seen in the overall average APL and 'local' APL. While still performing above average compared to all networks, these values are not as high as for the high k proximal point network or the Delaunay triangulation. However, given the loss of a number of links the increase in the 'local' APL is not as great as one would expect, deduced from the network having the greatest deviation below the regression line of those variables. Summarising, the Gabriel graph can be a good alternative to the Delaunay triangulation as a representation of a local transport network directed at the *castella*, losing the negative points while retaining the 'local' APL relatively well.

6.2.6.10 *Efficiency networks*

Among the network construction techniques studied, the efficiency networks are really the most experimental and perhaps least predictable ones. First, they are always entirely connected as the minimum spanning tree is used for the initial construction. Evidently the minimum spanning tree itself proves to be a very inefficient network to represent local transport, but it is valuable to consider it as a reference point to which the developments in the efficiency network can be measured. After increasing the number of links by 10% with respect to the minimum spanning tree, the network still performs quite poorly in terms of APL and 'local' APL, which can be attributed to the still low number of links present in the network. Further growing the link count to an increase of 25% and 50% ultimately results in a better 'local' APL, yet not good in comparison to other networks. This is unsurprising given the still comparatively low number of links, and the good position of the 50%-network with respect to the regression line gives reason to expect further increases in the number of links to have a relatively large further decrease in overall average 'local' APL. Another interesting property of these networks is the very low average clustering coefficient in the network in combination with a reasonable network heterogeneity. This may result in a better identification of central nodes in the network as there are fewer large clusters where nodes have relatively similar centrality measures. A practical downside of the efficiency network as a construction technique is the computation time, given that the dataset consists of $524 \times 523/2 = 137{,}026$ potential links, and that the efficiency improvement these links provide may change after the addition of each link to the network. In conclusion, the efficiency network may be a good option to represent local transport networks connecting the rural settlements to the *castella*, and has some network properties that have interesting implications for the application of further network analysis. Its value may be increased even further if the number of links added to the network is increased (e.g. to 60%) to levels comparable to the Gabriel graph for example, but unfortunately this is hindered by the time it takes to compute these networks.

6.2.6.11 *Final comparison*

Having drawn preliminary conclusions on all networks, an overall verdict can be given on how well these network construction techniques achieve the stated goal: a representation of a local provisioning system that connects the rural settlements to the *castella*. The Gabriel graph appears to be the network that is able to perform good in terms of 'local' APL without big downsides. A good alternative is the proximal point network with a high k if the relatively high average degree is not considered a problem. The efficiency networks that were studied were not able to compete in terms of 'local' APL, but the technique has the potential to be a good representation of a local transport network if the number of links added in the algorithm can be further increased. Delaunay networks perform well over the measured network metrics, but have the downside of including many links that are realistically not supposed to be part of the representation that is aimed for, as well as not being able to include temporal distances in the initial construction. Maximum distance networks have proven to work well in a local case study, but do not function on this scale where site density is very heterogeneous.

6.2.7 Conclusion

Extending on previous research on the importance of the choice in network construction techniques, the study presented in this section aimed to compare various techniques to find which one provides the best representation of a potential local provisioning system that links rural settlements to military *castella* in the Dutch part of the Roman limes, given the existing dataset of least-cost paths between all settlements in the region. In order to evaluate this, the average path length and 'local' average path length to reach the *castella* were used as primary metrics, next to other indicators such as number of links and average degree, as well as a more qualitative look on the general network structure. The Gabriel graph and proximal point networks with a high k were shown to be the most likely candidates to represent the desired local transport network, with proximal point networks with a low k, maximum distance networks, a Delaunay triangulation and the modelled efficiency networks all having more downsides. As a final conclusion, this study has confirmed what has been posited earlier by Rivers *et al.* (2013), namely that the choice of a network construction technique is important and must be a conscious decision based on the archaeological case it aims to represent, and it has presented a possible strategy through which such a decision can be made.

6.3 Uncertainty and robustness analysis[2]

6.3.1 Introduction

The application of network approaches and network analysis on reconstructed networks offer additional information on the network structure that cannot be deduced qualitatively from looking at the network maps (Verhagen *et al.* 2013a, 364), and for this reason we have applied these approaches in our earlier research on local transport in the Dutch part of the Roman *limes*, with some promising results and interpretations regarding the functioning of the local transport network and the role of certain archaeological sites within that network (Groenhuijzen and Verhagen 2015). However, previous studies in transport network modelling, including those referenced above, have paid little attention to the validation of network analysis results.

In social network analysis (SNA), Peeples and Roberts (2013) did a sensitivity analysis on the construction of binary networks from continuous data, showing that many network measures used for social interpretations are influenced by the assumptions on which the network is

[2] The content of this section was published earlier in slightly modified form as **Groenhuijzen, M. R., and P. Verhagen. 2016. "Testing the Robustness of Local Network Metrics in Research on Archeological Local Transport Networks."** ***Frontiers in Digital Humanities*** **3. doi: 10.3389/fdigh.2016.00006**, the only difference being the modified introduction, a shorter introduction on the datasets, and minor rephrasing. Research design by MG and PV; data provided by MG and PV; analysis by MG; discussion and conclusion by MG.

constructed. Research on the stability or robustness of centrality measures has shown that these measures become less stable under the introduction of imperfect data (Borgatti *et al.* 2006) and when sampling the network dataset (Costenbader and Valente 2003).

Based on the aforementioned research in SNA it can be argued that without sufficient validation the results of network analyses are only really valid for the particular networks being analysed, and can potentially be quite susceptible to minor changes in the networks. This may be the case when archaeological sites are missing from the dataset, when sites are not correctly dated and/or interpreted, or when there are uncertainties in the least-cost path reconstructions. In order to gain a critical understanding of our network analysis results and to tackle the overlooked topic of validation in archaeological network analysis in general, this section aims to test the robustness of network metrics in transport networks, in particular that of betweenness centrality, by investigating how they develop when the analysed network randomly emerges. Since betweenness centrality in archaeology is often seen as an indicator of a site's importance in a network (Brughmans 2013b, 636–38), we expect it to be relatively robust, which we define as the network measure stabilising before the network is completely formed, because betweenness centrality should be an inherent property of the site's position in the landscape and in the transport network, even when not all sites or connections in the network are present. In this way, by validating the network analysis results we also aim to test the robustness of the archaeological interpretation thereof.

6.3.2 Data

This study follows our earlier published study on the Kromme Rijn region on modelling different transport modes and the application of tentative network analysis (Groenhuijzen and Verhagen 2015; see also section 5.3), and thus is applied on the same datasets. It uses the archaeological site dataset, including both settlements and other types of sites, and modelled datasets of local transport connections (Chapter 5), including regular foot travel (hereafter W0), foot travel while carrying 40 kg (W40), mule-cart (MC) and ox-cart (OC) transport. Similarly to the earlier study on the Kromme Rijn region, networks were created from the least-cost path dataset following the maximum distance principle with a cut-off distance of 60 minutes (see section 6.2.3.1; Groenhuijzen and Verhagen 2017). The datasets are filtered for the Middle Roman Period (AD 70-270) according to the original chronology assigned to the sites (see section 3.4). The reinterpreted chronological information established in section 3.4.2 and Verhagen *et al.* (2016b) was not used since this was not yet available at the time this study was conducted, but the methodology is replicable and thus can potentially be applied in future studies with this dataset and other datasets. While this research focusses on the Kromme Rijn region because this area was also the focus of the directly preceding study, the methodology in principle is extendable to other areas.

6.3.3 Methodology

Transport networks modelled and analysed in the earlier study (Groenhuijzen and Verhagen 2015) showed some potential for use in archaeological questions related to the structure and properties of the network, its development through time and the role of individual sites within it. However, the analysis was always applied on a complete network, and the results could thus be dependent on that specific network structure existing. In other words, the network measures could change significantly if there are even minor changes in the network. Of course, in archaeological studies of this kind we can never be completely certain that we have captured the complete network at a specific point in time: our site inventories are never complete and are subject to uncertainties in dating, interpretation and in the least-cost paths calculated. It would therefore be a valuable exercise to test the robustness of the network analysis results and thus the validity of network measures even when applied to an incomplete dataset, by seeing how they evolve in a randomly emerging network. In contrast to the concept of random graphs (Barabási and Albert 1999), however, all sites and paths in this study are predetermined, only the order in which they appear is random.

In the previous study (Groenhuijzen and Verhagen 2015) we have used betweenness centrality to compare the position of the sites in the modelled networks. Betweenness centrality (C_B; Freeman 1977) is a local network measure that calculates how many shortest paths between all pairs of other nodes must pass through the node considered. As presented in section 1.4.6.6, it is calculated for a node (v) by dividing the amount of shortest paths (p) between two other nodes (s and t) that pass through node v by all shortest paths between nodes s and t, and repeating this for all pairs of other nodes (Eq. 6.2).

$$C_B(v) = \sum_{s \neq v \neq t} \frac{p_{st}(v)}{p_{st}} \qquad (6.2)$$

Since the outcome of this function scales with the number of nodes in the network, betweenness centrality is often normalised by dividing it by the number of pairs that don't include the node v, wherein n equals the total number of nodes (Eq. 6.3).

$$C_{B\ normalised}(v) = \frac{2 \times C_B(v)}{(n-1)(n-2)} \qquad (6.3)$$

The normalisation was also applied in this study. The calculation of betweenness centrality is further illustrated with an example network in Figure 6.19: the central nodes control all shortest paths between the other nodes of its own cluster (with the sole exception of the single path that connects to the outlying node) as well as all shortest paths between their cluster and the opposite cluster, giving it a high betweenness centrality ($C_B = 0.69$). In contrast, the nodes with $C_B = 0.22$ only control the paths towards the outlying node, and all other nodes control no shortest paths ($C_B = 0$). From an archaeological perspective betweenness centrality is thus often interpreted as the amount of control that a site has over movements along certain transport corridors, for example in a study of the relative importance of key towns within a transport network of Roman Baetica (Isaksen 2008) or in a study aiming to infer gateway sites in the maritime networks of the Southern Aegean in the Middle Bronze Age (Rivers *et al.* 2013).

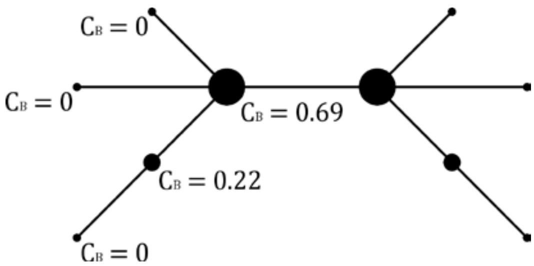


Figure 6.19. Betweenness centrality in an example network.

In order to test the robustness of betweenness centrality measured in the 'complete' network, a model was written using NetLogo 5.2.0 (Wilensky 1999), a programming language and modelling environment primarily known for its use in agent-based modelling studies. Although this study is not agent-based, the versatility of the program with its GIS- and network-plugins as well as the capability to easily perform parallel runs using the BehaviorSpace module makes it a preferable choice. However, the necessary procedures can be written in other programming languages such as Python or Java as well. The model and a model description according to the ODD protocol (Grimm *et al.* 2006; 2010) are included in Appendix 5.

The model (Fig. 6.20) requires only the existing site dataset and one of the four modelled transport network datasets, both of which can be filtered if so required. A model run starts with only one site being present, which is considered the key site in that run for which the robustness of betweenness centrality is measured. All other sites and links are marked as 'absent'. The model then randomly takes five other sites from the dataset, marks them as 'present' and adds all paths between the present sites. The number of five sites added per step as opposed to only one site was chosen to increase the speed of model runs, without losing too much detail. The betweenness centrality of the key site is subsequently recalculated based on the present network using the 'betweenness-centrality' procedure from NetLogo's network extension. The algorithm used in this procedure comes from the JUNG software library (White and Nelson 2009) and is based on the algorithm proposed by Brandes (2001).

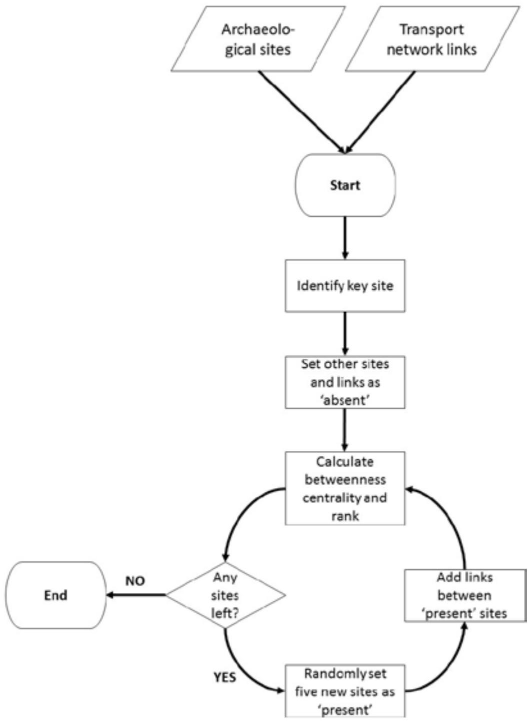


Figure 6.20. Flowchart representing the model schedule of one run for a single site.

Besides betweenness centrality, the betweenness rank is also measured. Betweenness rank in this study is defined as the measure of a site's betweenness centrality in relation to all other sites: the site with the highest betweenness centrality is given a value of 1 and the site with the lowest betweenness centrality a value equal to the number of sites present (up to 242 in this study). The ranking of sites in this way can be used to compare the role that an individual site has within the network against other sites. Additionally, a distinction is made between absolute betweenness rank (i.e. the rank in relation to the total number of other sites in the network) and the percentage betweenness rank (i.e. the percentage of measured sites that have an equal or higher betweenness centrality). The latter measure is used specifically to characterise the stability of a site's role in the network throughout a model run. This distinction is important, as before the end of a model run not all sites are present in the network, and both betweenness centrality as well as absolute betweenness rank are still subject to change while the percentage betweenness rank may already have stabilised. For example, a site ranking 10 out of 100 will have a percentage rank of 10%, indicating that 9 sites have a higher betweenness centrality, and 10% of sites have an equal or higher betweenness centrality. When later in the model run the same site ranks 20 out of 200, the percentage rank is still 10%. So while the percentage rank in this example has stabilised at 10%, the absolute rank has in fact declined from 10 to 20 due to the presence of more sites. This illustrates that the distinction of a percentage betweenness rank is necessary to establish the robustness of a site's role in the network.

The process of adding sites and recalculating the local network measures is repeated until all sites and paths from the dataset are added to the network, meaning that each run will converge towards the same end-result. Each site is subjected to 100 such runs to account for the variability between individual runs. In this study, the site dataset is filtered to include only sites dating to the

Middle Roman Period (AD 70-270) and each site is tested in all four transport network datasets, each filtered to include only connections that can be travelled within one hour.

For each site in each transport network the betweenness centrality and absolute and percentage betweenness rank are recorded during the model runs. The mean development of these across 100 runs are plotted in graphs, and subsequently assigned to groups according to the following characteristics of the graphs: presence/absence of a convex break in the percentage betweenness rank, presence/absence of stabilisation of the percentage betweenness rank and the timing of this stabilisation. These are established using an approximation of the first derivative of the data. Stabilisation is defined here as the moment (expressed in number of sites added in the model) that the rate of change of the percentage betweenness rank is less than 1 percentage point and the measure is continuously within 1 percentage point of the end-result.

6.3.4 Results

The complete model output and analysis results can be found in Appendix 6. The graph types distinguished will be further discussed here. Type A covers graphs that have a quick early rise in percentage betweenness rank and a convex break and subsequent stabilisation in the percentage betweenness rank decline. This group is further subdivided into type A1, A2, A3 and A4 (Figs. 6.21-24), all of which have the aforementioned pattern but represent very early (after <101 sites in the model run), early (101-150 sites), middle (151-200 sites) or late (>200 sites) stabilisation of the percentage betweenness rank respectively.

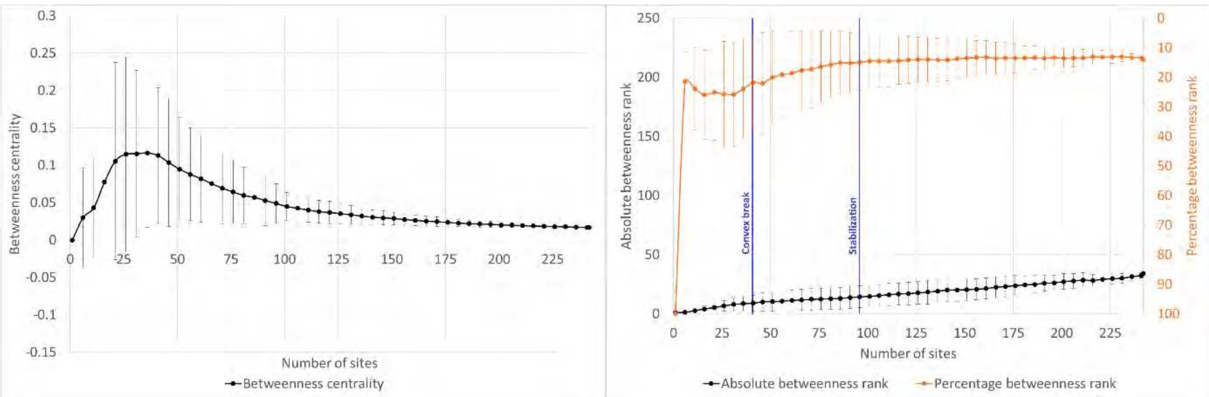


Figure 6.21. Example of type A1: site 461 (Houten-Odijkerweg in the W0-network).

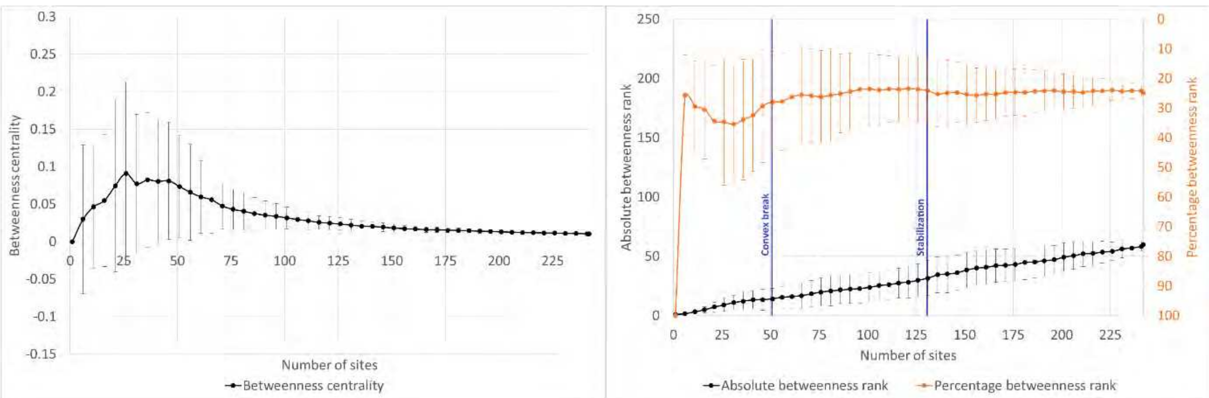


Figure 6.22. Example of type A2: site 488 (Houten-De Geer in the W0-network).

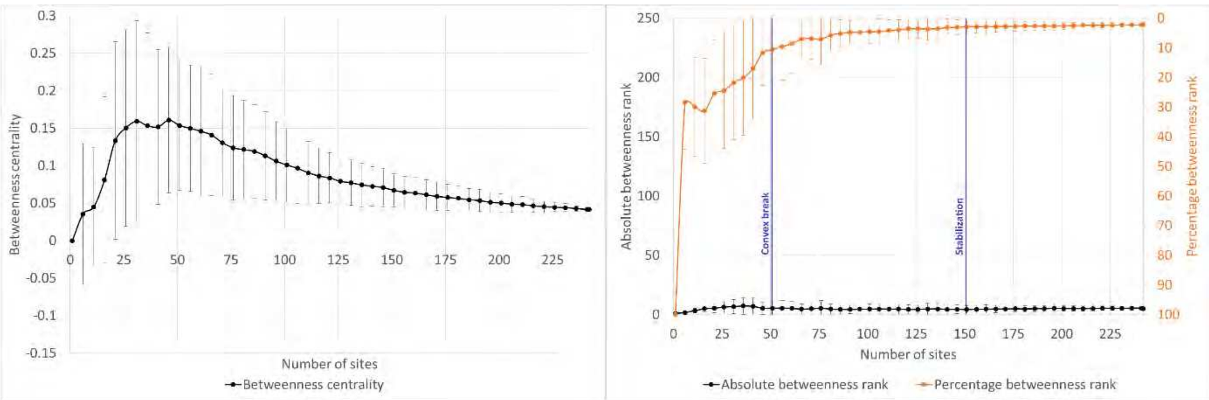


Figure 6.23. Example of type A3: site 3154 (Utrecht-Amerikalaan in the W0-network).

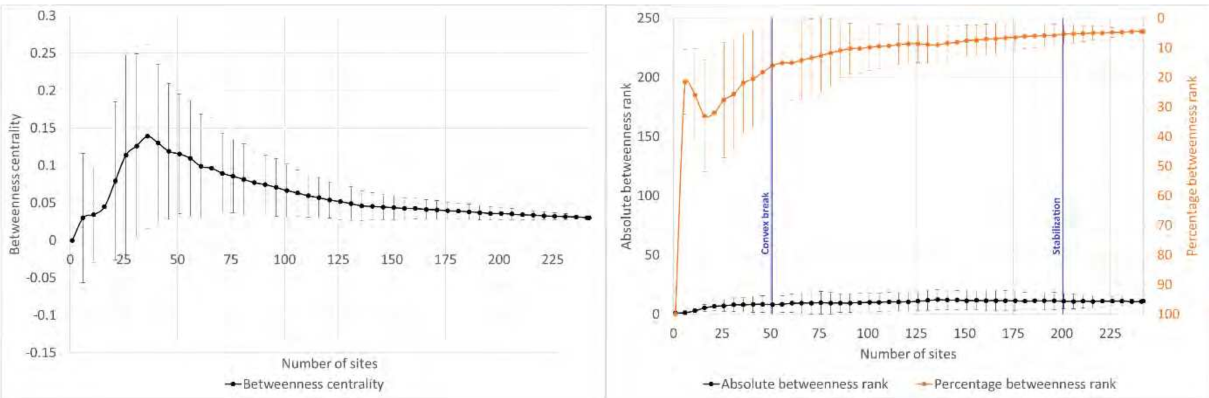


Figure 6.24. Example of type A4: site 112 (Houten-Tiellandt in the W0-network).

Type B (Fig. 6.25) is similar to type A in that it has a convex break in percentage betweenness rank, but they differ in that there is no stabilisation of the percentage betweenness rank. In many cases it can be seen as a natural continuation of type A4, as there often is a trend of levelling-off towards stabilisation visible in the percentage betweenness rank.

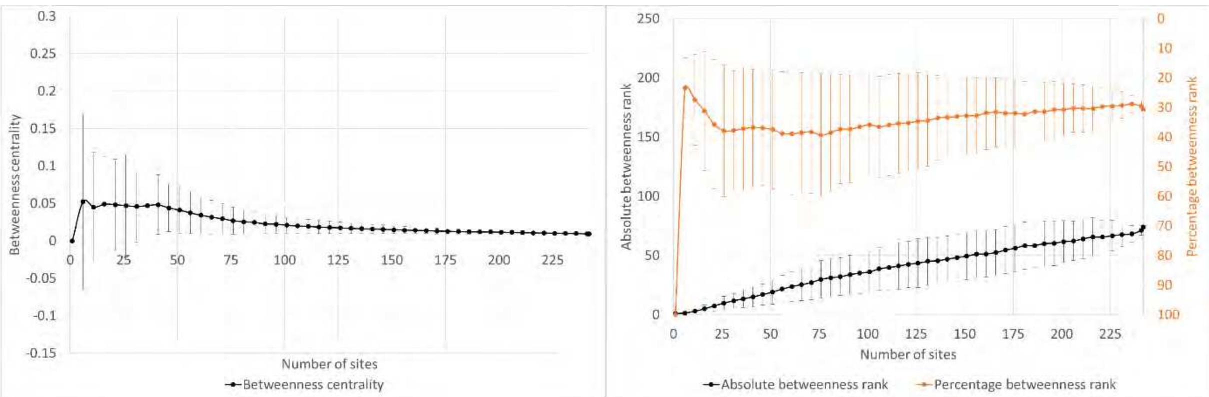


Figure 6.25. Example of type B: site 470 (Werkhoven-Hollende Wagen II in the W0-network).

Type C (Fig. 6.26) is characterised by a concave declining percentage betweenness rank and an ultimately increasing absolute betweenness rank, and no stabilisation of the percentage betweenness rank. Type D (Fig. 6.27) shows a convex increasing percentage betweenness rank, a declining absolute betweenness rank and similarly no stabilisation of the percentage betweenness rank.

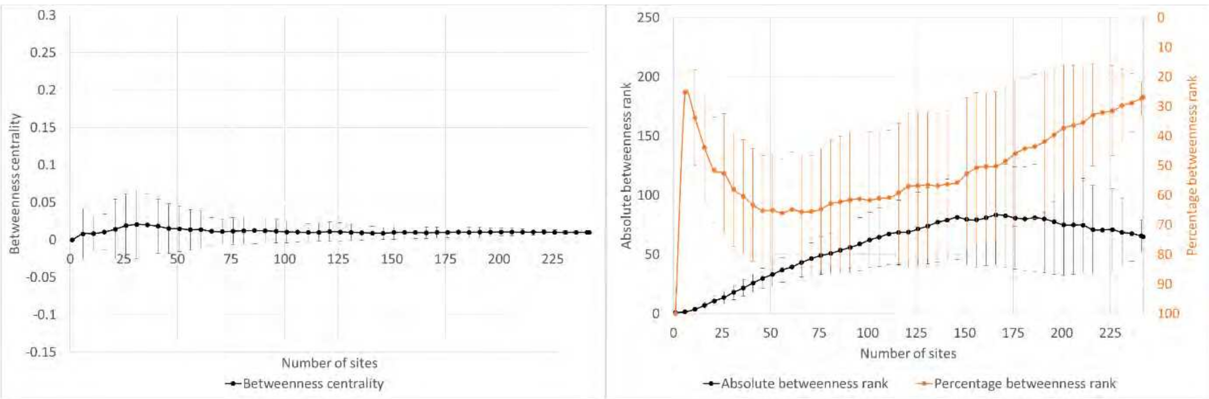


Figure 6.26. Example of type C: site 4016 (De Meern-Zandweg in the W0-network).

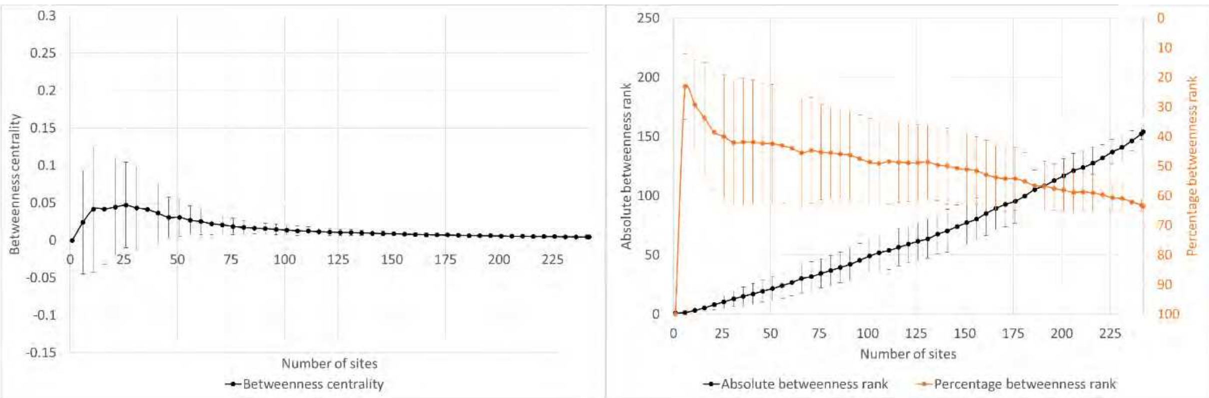


Figure 6.27. Example of type D: site 434 ('t Goy-Nachtdijk I in the W0-network).

Type E (Fig. 6.28) is a final anomaly, which covers sites that have no (or very few but insignificant) paths connected to it, so that its betweenness centrality is rendered 0 throughout the model run.

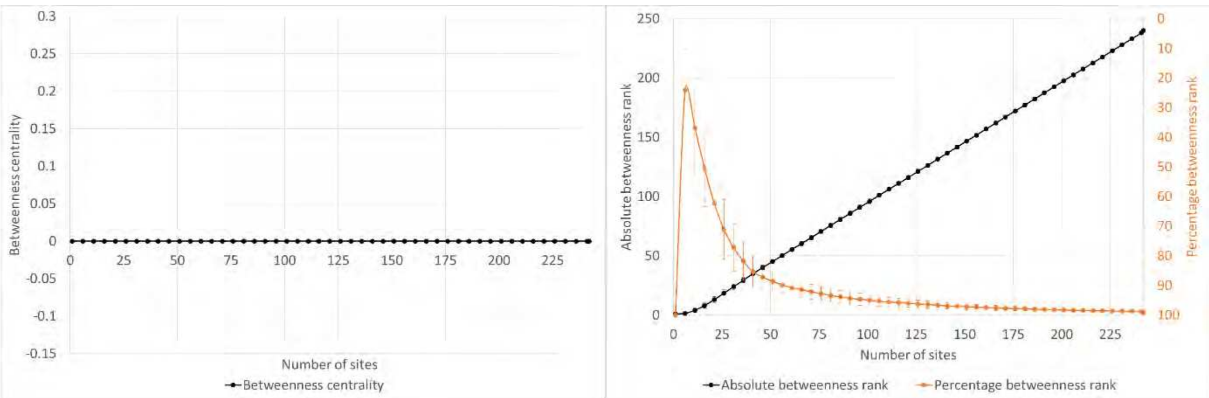


Figure 6.28. Example of type E: site 547 (Rijswijk-Roodvoet in the W0-network).

Table 6.5 shows the distribution of the experiment results across the distinguished groups. The majority of measurements fall into one of the type A groups, with type A4 being the most prevalent. It is not very common for sites to belong to a single group in all four transport networks, occurring only 30 times out of 242 sites, as shown in Table 6.6. A total of 57 sites belong to any type A group in all four transport networks.

Transport network	A1	A2	A3	A4	B	C	D	E	Total
W0	2	12	32	131	51	9	2	3	242
W40	0	1	13	115	72	16	14	11	242
OC	0	3	14	123	52	23	13	14	242
MC	2	12	21	140	53	9	1	4	242

Table 6.5. Type group membership of all site measurements across the four transport networks.

A1	A2	A3	A4	B	C	D	E	Total	Any A
0	0	0	24	2	1	0	3	30	57

Table 6.6. The frequency of a site belonging to a single type group across all four transport networks.

An interesting subset of sites constitutes the top 10% of sites in terms of betweenness centrality or absolute betweenness rank, as a high betweenness centrality is often associated with archaeological implications about the role of that site in the network. As shown in Table 6.7, the majority of sites belonging to the top 10% in each respective network can be categorised into type A groups.

Transport network	A1	A2	A3	A4	B	C	D	E	Total
W0	0	2	10	12	0	0	0	0	24
W40	0	0	1	17	1	5	0	0	24
OC	0	1	2	14	3	4	0	0	24
MC	0	2	9	8	2	3	0	0	24

Table 6.7. Type group membership of sites within top 10% of betweenness centrality/absolute betweenness rank for each individual transport network.

Some more patterns can be observed when looking at the other deciles of the distribution of absolute betweenness rank, as shown in Table 6.8. Type groups A2 and A3 are significantly (>1 standard deviation from the mean) more abundant in the first decile, which constitutes sites with an absolute betweenness rank between 1 and 24. Type group A2 is also more abundant in the third decile (49-72). In general, type groups A2 and A3 are more abundant in the top 50% (1-120) and less abundant in the bottom half (120-242). Type group C is significantly more abundant in the second decile (25-48). Moreover, it is generally more abundant in the top half and virtually absent in the bottom half. On the contrary, type group B is significantly less abundant in the first decile and significantly more abundant in deciles of the bottom 50% (121-144 and 145-168). Type group D is significantly more abundant in the same subsets, and virtually absent from the top half

(1-120). As can be expected, type group E is limited to the last decile (217-242), as this type is characterised by a betweenness centrality of 0.

Betweenness rank decile	A1	A2	A3	A4	B	C	D	E	Total
1-24	0	*5	*22	51	*6	12	0	0	96
25-48	*1	2	10	45	15	*23	0	0	96
49-72	0	*7	9	51	22	8	0	0	97
73-96	*1	4	9	51	22	5	2	0	94
97-120	0	4	10	53	20	5	4	0	96
121-144	*1	1	6	43	*35	2	*8	0	96
145-168	0	1	4	*34	*45	0	*11	0	95
169-192	0	1	3	58	30	2	2	0	96
193-216	*1	1	5	58	28	0	3	0	96
217-242	0	2	*2	*65	*5	0	0	*32	106
Mean	0.39	2.8	7.94	51.06	22.59	5.65	2.96	3.5	
St. deviation	0.49	1.99	5.45	8.36	11.86	6.85	3.57	10	

Table 6.8. Distribution of site measurements over decile subsets based on absolute betweenness rank, in all four transport networks. The total number of sites per decile can deviate due to sites being tied in rank. Mean and standard deviation are weighted according to population sizes. Cells with an asterisk indicate values deviating from the mean by more than one standard deviation.

6.3.5 Discussion

The categorization of the modelling results into clearly characterised graph types allows for the comparison between the resulting groups and their significance for the archaeological interpretation of network analysis results. When discussing transport networks, it may be argued that the position of a site in its networks of trade, exchange and/or social movement is the result of a gradual natural evolution over time. This is particularly so for a site that plays an important role in that network, and perhaps was even established on that location because of its favourable position in existing transport networks. As has been stated in the introduction, we should thus expect the betweenness centrality, especially for important sites, to be relatively robust even when the network is not fully complete, as it is an inherent property of the site's position in the landscape and in the network. Robustness in this instance would mean that the position and role in the network, as represented by betweenness centrality rank, stabilises before the network is completely formed rather than it being the end-product of the entire network.

Following this line of thought, robustness is thus true for the sites that belong to type group A. Among the 242 sites in the four different transport networks, these types occur a total of 621 times, or roughly 64%. Types A2 and A3 are generally more prevalent among sites with a higher betweenness centrality and betweenness rank (as shown in Table 6.8), whereas types A1 and A4 are less distinctly distributed. This indicates that to some extent robustness is higher among sites that occupy more important positions in the network based on betweenness centrality, although the more uniform distribution of type group A4 shows that this is not a rule. For the occurrences of types A among the sites it can be argued that the measured betweenness centrality is an inherent property of the site's location and not dependent on the presence of the complete network nor susceptible to small variations in the network. When a site with a high betweenness centrality belongs to type group A, it also adds robustness to the archaeological interpretation that it has a certain amount of control over movement in the transport network. The site attracts transport because it occupies a strategic location in the landscape, but it also occupies a position in the network that attracts transport because it is between other sites. Although difficult to substantiate without strong archaeological evidence, some site locations may have been chosen because of their favourable location in transport networks.

When looking at the top 10% of sites based on betweenness rank (Table 6.7), the amount of sites ascribed to type group A even rises to 78 out of 96 sites, or roughly 81%. This indicates that sites that were recognised as 'important' gateway sites in the least-cost path networks are more likely to have a betweenness centrality that is inherent to the site's location and independent of the presence of the entire network. The relative high share of robust sites among the top 10% at least adds some degree of security regarding the archaeological interpretation of network analysis results, considering that it often focuses on the most important sites rather than the least important ones, and that a site's profitable position between other sites in the landscape is often used as an explaining factor for its importance (e.g. Groenhuijzen and Verhagen 2015).

The sites belonging to other type groups require a different explanation. Among these, type B is most prevalent. As has been mentioned, this type shows similarities with and can be seen as a natural successor to type A4, with a trend of levelling-off towards stabilisation in the final stages of the percentage betweenness rank development, without stabilising entirely. Based on this tendency it can be argued that similarly to type A4 the betweenness centrality of the site's location is partly an inherent property, but is still susceptible to variations in the network. It might also be an indication that the site's position is not entirely a result of a naturally favourable location in the landscape and the network, but that other factors also played a role. This could be the case for instance for some Roman watchtowers (468, Werkhoven-Klaproos; 785, De Meern-De Balije; 835, De Meern-Veldhuizen), which are located on corridors on a stream ridge or between two stream ridges. Apparently these sites occupy a strategic position in the landscape attracting some transport, but as opposed to sites of type A, they are not attracting much transport in the network due to their relative peripheral location from other sites. This position in the landscape and the network gives sites a tendency towards a stable betweenness centrality, but not a convincing stability as sites of type A as there are likely other (non-natural) factors that played a role in establishing its location. However, since this type is shown to be susceptible to minor changes in the network (albeit not as much as the following types C and D), archaeological interpretations cannot be thoroughly substantiated without first determining the validity of the precise network layout itself.

Type C and D are a different matter, as they show no stabilisation or signs of a trend towards it. It suggests that their betweenness centrality as measured in the complete network is not the result of their natural position but is very reliant on all other sites being present in the network. This can indicate that the site's location is not governed by a strategic position in the landscape or a favourable location in the network. Instead, its location is more likely to be influenced by other factors, such as landscape suitability for certain activities (e.g. agriculture, animal husbandry) or even external causes such as Roman military policies. The latter is found for example in some watchtowers (4016, De Meern-Zandweg) and a *castellum* (4067; Woerden-Hoochwoert I). There seems to be a distinction between type groups C and D in that the former mostly includes sites with a higher betweenness centrality and rank, and the latter includes mostly sites with lower betweenness centrality and rank. Type C is characterised by an increasing absolute betweenness rank, indicating that this represents a site that becomes more and more important in terms of control over movements in the network, simply because the number of sites and thus the number of movements increases. This is contrasted to type D, in which sites become less and less important as the network grows. This can be explained by the sites' positions along the margins of the research area, and as a result also along the margins of the network. Type D thus can be useful to identify sites affected by edge effects.

Type E is an anomaly which can only be found among sites that are either disconnected, or have very few connections that are not travelled as shortest paths between other sites. This results in a betweenness centrality of 0 and thus the lowest betweenness rank in all model runs. It occurs primarily in transport networks representing slower and less versatile modes of transportation such as ox-cart movement and walking while carrying a heavy load, which limits the number of paths in the network.

When comparing the results between transport networks it becomes clear that networks with more connections, which are the ones that represent faster and easier travel (W0 and MC), also have a larger number of sites belonging to the stabilising type group A. The robustness of betweenness centrality measurements in the other networks (W40 and OC) is reduced by the lower number of total connections, allowing for more variability as the network is not yet complete. It clearly shows that robustness of betweenness centrality measurements is determined by the interconnectedness of the network, which seems valid as by extension a completely connected network will also have a perfect robustness of network analysis measurements.

It is difficult to observe differences on a more detailed level such as by site type, since only a few sites have been excavated in detail and the majority (185 out of 242) of sites in the dataset are described as (rural) post-built settlements. Since the sample sizes of other site type groups are so small in comparison, detailed statistical comparisons are likely invalid. Some general patterns can be observed, such as the Roman *castella* (forts, $n = 6$) occurring mostly in type groups B, C and D, or *horrea* (storage facilities, $n = 3$) occurring in type groups A2 and A4. When considering the trade or taxation system that was installed by the Roman authorities to supply the military population, this could suggest that the horrea were constructed to replace or complement the marginally located *castella* as more centrally located gathering sites in robust and important places in the transport network, in order to improve efficiency of gathering resources. Such a hierarchical system of the flow of goods from and to the primary centre(s) matches the socio-economic system proposed earlier for the region, involving also the *vici* near the Roman *castella* and the stone-built and large post-built rural settlements (Vos 2009, 228; Willems 1986, 421). Stone-built rural settlements ($n = 8$) do not appear to behave differently from all other sites, having a robust betweenness centrality as part of one of the type groups A in 20 out of 32 measurements (~63%). However, it must be noted that stone-built rural settlements are more likely to belong to the top 10% of sites in terms of betweenness rank, occurring in 8 out of 32 measurements (25%). In our previous research we already acknowledged this phenomenon, and explained it by the stone-built settlements being on important bottleneck sites or junctions of river levees, locations that naturally attract transport, allowing the sites to grow in status and/or wealth (Groenhuijzen and Verhagen 2015, 39). This matches archaeological expectations as the hypothesis was already proposed in an earlier study of the settlement landscape of the area (Vos 2009, 233), and supports the idea referenced earlier that at least some of the stone-built settlements play an important role in the hierarchic socio-economic structure of the region.

The results of testing the robustness of betweenness centrality in this case study has implications for applying network analysis on archaeological transport networks, and by extension for network analysis applications in general. As was demonstrated, a majority of sites (~64%) belong to one of the type groups A, representing a stabilisation of network measurements in the model. These are not very susceptible to changes in the network for example due to sites missing, sites being incorrectly interpreted or uncertainty in the path reconstructions. This number rises to ~81% when only considering the 10% of most important sites in terms of betweenness centrality. However, a significant number of sites are categorised in one of the non-stabilising types. This is not restricted to sites with low betweenness centrality but also still occurs among sites with high betweenness centrality, as is shown in Table 6.8. This has serious implications for the archaeological interpretation of network analysis results, as the results are apparently dependent on that precise network structure being present. While the results for sites of type A can be considered robust and thus trustworthy enough to warrant an archaeological interpretation of their role in the network, this is not the case for the considerable amount of other sites (~36%).

6.3.6 Conclusion

In this study the robustness of betweenness centrality measurements in archaeological local transport networks was tested. By using a model that randomly adds sites from the dataset to the network, the development of betweenness centrality was measured. The results could be categorised into graph types expressing different development patterns. Across all networks analysed approximately 64% of sites belong to type group A, which represents a stabilisation of the network measurements prior to the entire network being present. Betweenness centrality for these sites can thus be interpreted as being robust and not dependent on the full network structure being present, which also makes the archaeological interpretations concerning the role of such sites in the network more reliable. Other sites cannot be characterised by stabilisation of the betweenness centrality measurements, meaning that they are susceptible to minor changes or errors in the network. Archaeological interpretations of the position of these sites in the network cannot be substantiated without first determining the (archaeological) validity of the network layout being measured, including the sites and paths being taken into account. To some extent the other distinguished types can be used for other purposes, such as determining sites that are affected by edge effects (type D). Testing robustness of network analysis results, such as betweenness centrality as demonstrated in this study, thus proves a useful tool both for validating the network modelling results themselves as well as the archaeological interpretations of the modelled network.

6.4 Applications of network analysis on transport within the *limes* zone

6.4.1 Introduction and early research

By constructing a network according to one of the network configurations discussed in section 6.2, the dataset of modelled transport connections now becomes accessible for a more quantitative study in the form of network analysis, of which the concepts and terminology were presented in sections 1.4.6.5-1.4.6.6.

Exploratory network analysis has been done earlier on the case study of the Kromme Rijn region and was published in Groenhuijzen and Verhagen (2015). In this study, transport networks were constructed for walking while carrying loads of 0, 20 and 40 kg (hereafter respectively W0, W20 and W40), as well as mule-cart transport (MC), by applying a simple maximum distance threshold (see section 6.2.3.1 for details) of 20, 30 and 60 minutes. This network construction technique was chosen on the assumption that journeys between two places normally consist of multiple smaller journeys between places that the traveller knows are on the way, and in this case all of those places are archaeological sites. This was shown to be appropriate for this case study area due to its relative homogeneous density of sites, but doesn't work so well for the Rhine-Meuse delta as a whole since that is much more heterogeneous, as is discussed in section 6.2.6.6.

The results of that study showed that under the maximum distance network principles the W0- and MC-networks are distinctly different from the W20- and W40-networks by being more connected, resulting in higher values in general network measures such as network centralisation, average degree, average path length and network density. This was interpreted as reflecting the unattractiveness of carrying heavier loads when easier methods of bulk transport (e.g. mule-cart) may be available (Groenhuijzen and Verhagen 2015, 38). Chronologically speaking, the increasing number of sites from the Late Iron Age through the Early Roman Period and the Middle Roman Period were shown to facilitate increases in average clustering coefficient and decreases in average path length, interpreted as a reflection of more complex and extensive social interactions in the region (Groenhuijzen and Verhagen 2015, 39).

On a more local level, a number of sites, particularly ones that connect multiple larger groups of sites through bottleneck locations, were shown to have a high betweenness centrality (Fig. 6.29). This was interpreted as these sites having a potentially large amount of control over movement in the network. Even more specifically, seven out of eight sites that were interpreted as stone-built rural settlements during the Middle Roman Period (out of a total dataset size of 180 sites) were shown to be in the top third of the W0- and MC-networks in terms of betweenness centrality (dark blue sites in Fig. 6.29). Five out of those eight were in the top third in the W20- and W40-networks. For the ones that already existed in the Late Iron Age and Early Roman Period (when all settlements were still post-built), the high values of betweenness centrality were already present, indicating that the stone-built rural settlements may have grown in status and wealth in part due to their favourable location in transport networks (Groenhuijzen and Verhagen 2015, 39). On the other hand, the *castella* of the Kromme Rijn region were rather marginal in terms of betweenness centrality, which is logical considering their relative peripheral location in the landscape and the network. This resulted in the interpretation that most movement in the Kromme Rijn region is likely to have occurred along the central levee rather than directly along the Rhine, making the *castella* and the Roman military road peripheral to transport on the local scale (Groenhuijzen and Verhagen 2015, 40), as was also discussed in section 5.3.

The exploratory research in the case study of the Kromme Rijn region (Groenhuijzen and Verhagen 2015) has shown that network analysis can be valuable to draw interpretations on the functioning of transport networks and the role of individual sites within those networks. In the remainder of this section 6.4 it is the intention to move forwards from these preliminary steps by more comprehensively applying concepts of network analysis on the entire dataset of sites and modelled transport connections in the Dutch part of the Roman *limes*, in order to tackle questions of transport in the limes such as those posed in section 6.1.2.

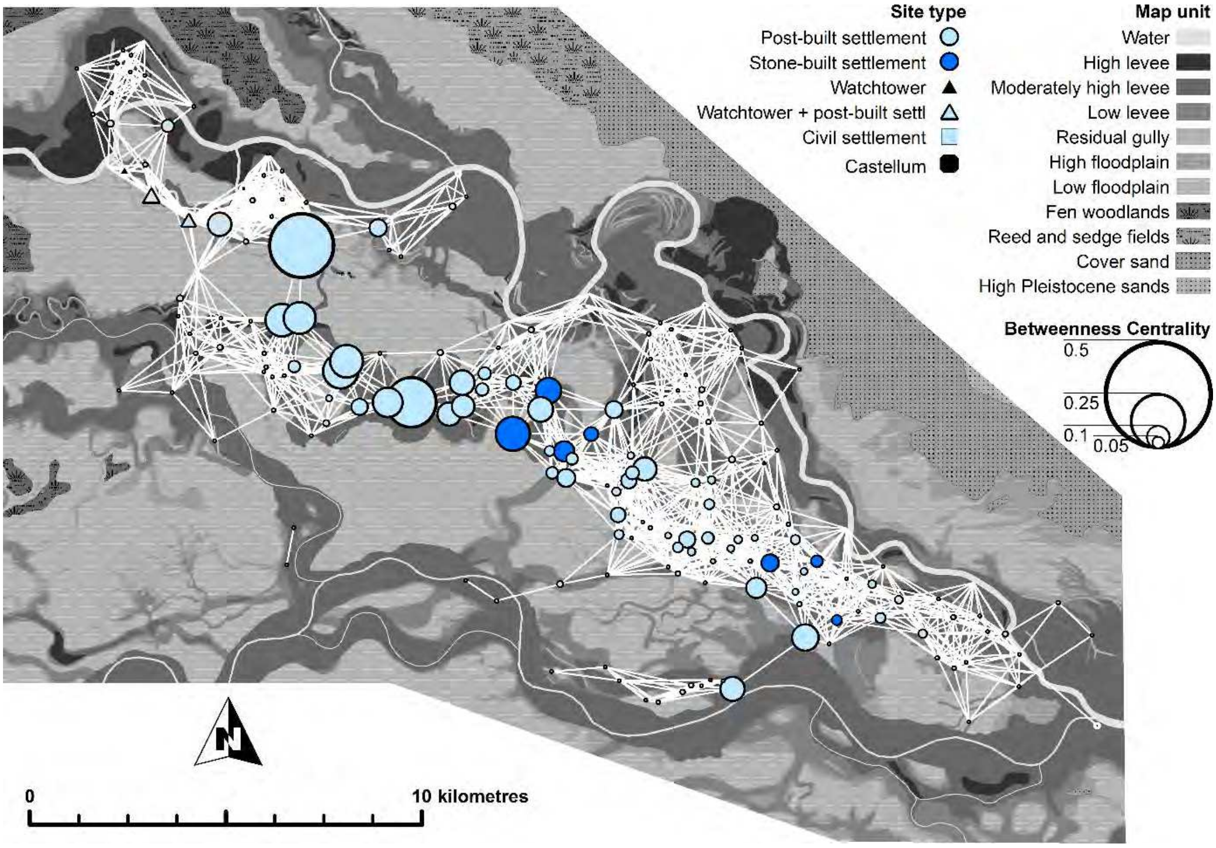


Figure 6.29. Betweenness centrality of sites in the MRP W0-network in the Kromme Rijn region. Some bottleneck sites with high betweenness centrality are visible in the top-left and centre-left. Stone-built settlements with a relatively high betweenness centrality are visible in the centre and bottom-right (from Groenhuijzen and Verhagen 2015, 37).

6.4.2 Data

The remainder of the analyses made in this section will use a uniform dataset that will be described here. The site dataset is filtered to only include sites interpreted as settlements that have a 50% or greater probability of being present during a certain time period, following the procedures discussed in section 3.4.2 and Verhagen *et al*. (2016b). This results in a dataset varying in size from 284 for the Late Iron Age (although this is most likely inaccurate since the original site dataset generally includes Late Iron Age sites only when they are continuous into the Roman Period) to 587 for the Middle Roman Period B.

Following the conclusions drawn from the research on network construction techniques presented in section 6.2 and Groenhuijzen and Verhagen (2017), the dataset of modelled transport connections is filtered to only include those that are part of the Gabriel graph, constructed using travel time for the separation between places (see sections 6.2.3.4 and 6.2.3.5) (Fig. 6.30). The main modelled networks that will be analysed here are walking while carrying a load of 20 kg (hereafter W20), and ox-cart transport (OC). As has been demonstrated in section 6.2.6.2, network results from the W20-network have a greater generality for other values of the carried load parameter as well (e.g. the W0- and W40-network), the only change being that the travel time values are scaled. The same goes for the MC-network with respect to the OC-network.

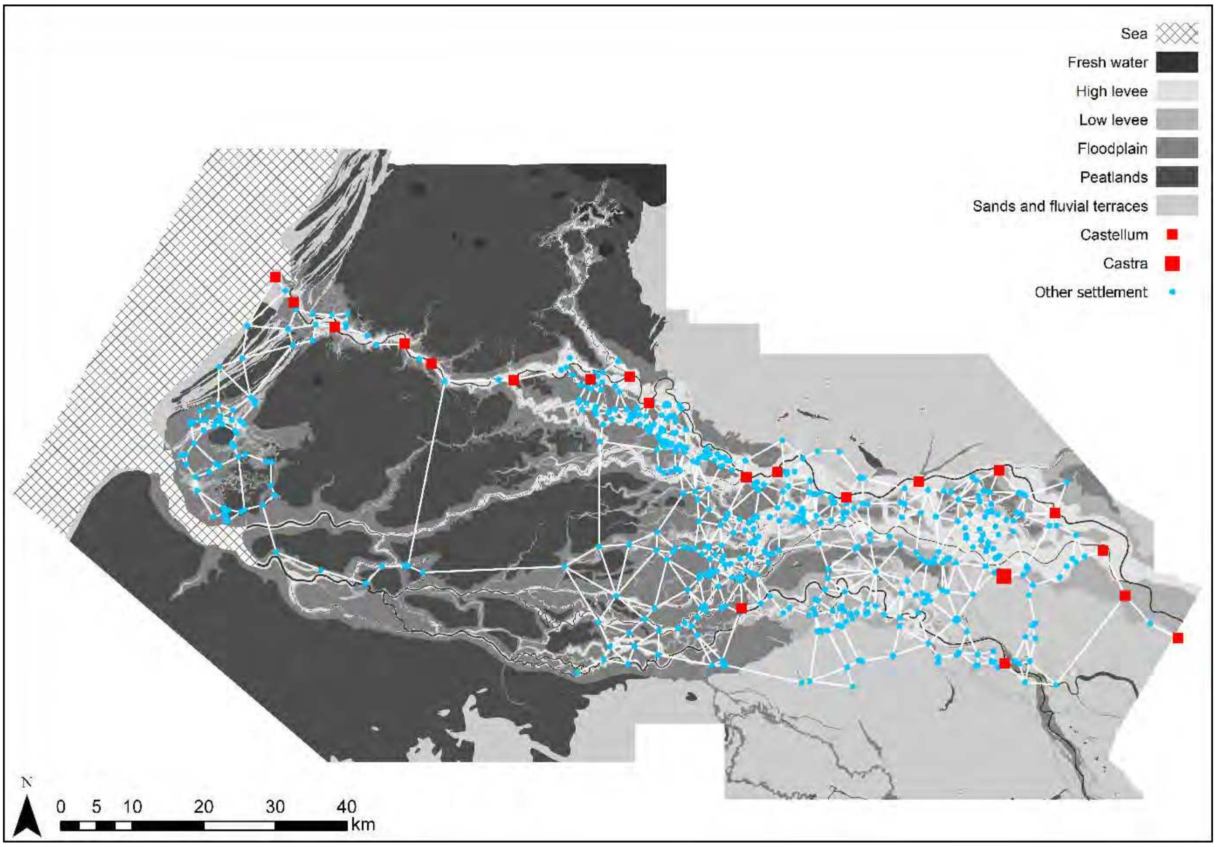


Figure 6.30. The Gabriel graph W20-network of the MRP A. The straight lines in this network are a simplified representation of the transport connections modelled through least-cost paths.

6.4.3 The flow of goods from the rural to the military population

6.4.3.1 Methodology

One of the key questions posed in section 6.3 regards the distribution of surplus goods from the rural population to the Roman military population occupying the *castella*. The implicit assumption that a certain amount of rural surplus goods ultimately flowed in that direction is founded on archaeological research (e.g. Cavallo *et al.* 2008; Groot and Kooistra 2009; Groot *et al.* 2009), but the exact manner through which this was carried out is not. Using the reconstructed networks of modelled potential transport connections, we can start to explore and experiment with hypotheses around this topic. Firstly, we can establish a null hypothesis that goods flowed directly from each settlement to a specific *castellum* (e.g. the nearest one) (Fig. 6.31A). This might be seen as a rather unrealistic hypothesis, as it implies that either the local inhabitants of each rural settlement moved their goods the entire direct way themselves regardless of distance to a *castellum*, or that members of the military population (e.g. Roman officials) travelled to each individual settlement to gather the required resources. However, such a null hypothesis can serve as a starting point to look at alternatives. For example, an alternative hypothesis can be posed that goods from individual rural settlements flowed to another more centrally located gathering point such as a storage facility, a local market, or in more general terms a 'local centre', from which it is likely that bulk transport destined for the *castella* can be more conveniently organised (Fig. 6.31B). This contrast can perhaps best be visualised by assuming that the transport of surplus goods towards the *castellum* requires one person to carry out one transport movement. For each settlement one person can in principal move all of his or her goods to the *castellum* directly, but it might be beneficial for a group of settlements to gather their products on a location nearby (either as a market or another gathering site) so that only one long distance bulk transport to the *castellum* has to be carried out from there. In that sense the hypotheses are thus testing the time advantage that one system has over the other.

The premise of the alternative hypothesis is that the most ideal gathering point should be one that is on average 'closest' to rural settlements, or at the least 'closer' than the gathering points in the null hypothesis, which are the *castella* themselves. The validity of this hypothesis will be explored in the following sections, particularly by comparing the *castella* against a number of settlements in the hinterland, including the towns and vici that are not associated with the forts along the Rhine, stone-built rural settlements and *horrea*. The latter two site types have been identified as special (sub)groups among the rural settlements in the site database (see section 3.3.2), and have previously been hypothesised to play a role in rural-military interactions (see section 6.1.2; Willems 1986; Vos 2009), as well as some additional settlements that have been identified by Vos (2009, 230, 235–36) as possible 'local centres' in the Kromme Rijn region by virtue of being larger than average rural settlements. This select group of settlements will hereafter be referred to as 'intermediary sites' (Fig. 6.32).

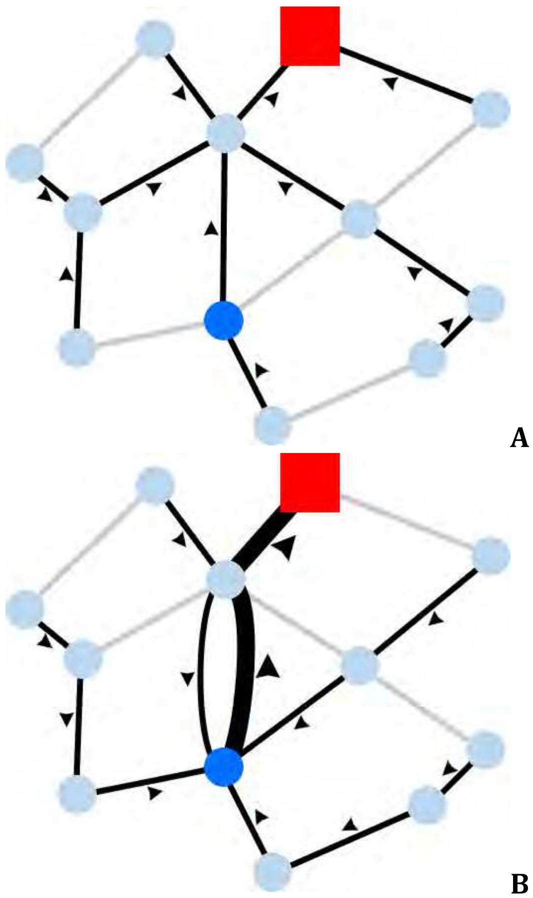


Figure 6.31. Schematic example of the null hypothesis and alternative hypothesis. A) All goods flowed directly to the castellum. *B) All goods flowed to the intermediary site, and were subsequently moved in bulk to the* castellum.

The hypotheses can be tested using path length, a concept of network analysis, which in the modelled transport network is expressed in minutes of travel time from one site to another over the links in the network. For the aforementioned alternative hypothesis to be valid, the expectation is that the total path length to reach an intermediary site (i) from a number of settlements (s) in addition to the path length of that intermediary site to the *castellum* (c) should be lower than the total path length to reach the *castellum* directly (Fig. 6.31). Since it is more likely that goods flowed to the nearest *castellum*, it is useful to only calculate the total path length for a number of nearest settlements, which for this study is set at 25 (see further below). When the alternative hypothesis is valid, that can thus also be expressed as:

$$TPL_{intermediary} < TPL_{castellum}, \text{ where:} \tag{6.4}$$

$$TPL_{castellum} = \sum_{s} L(s,c)$$

$$TPL_{intermediary} = L(i,c) + \sum_{s} L(s,i)$$

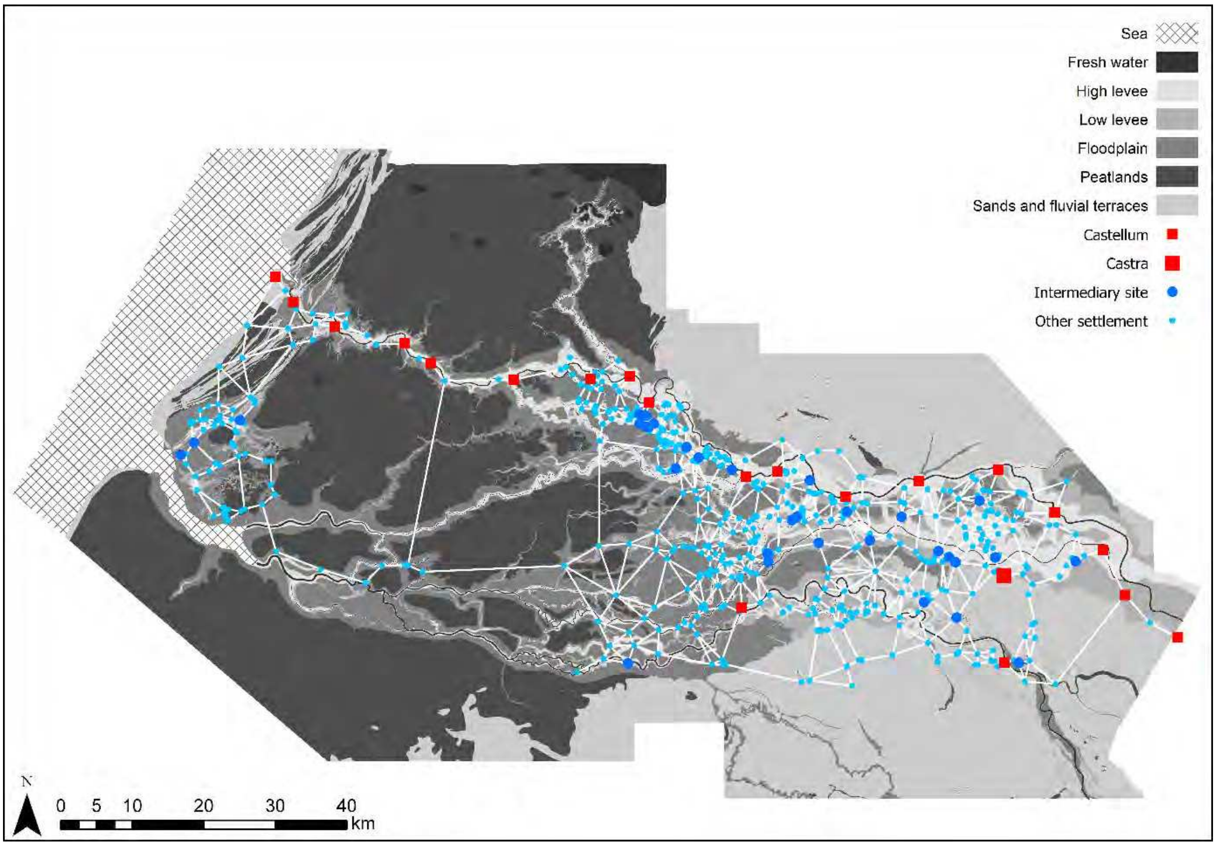


Figure 6.32. Overview of intermediary sites (in dark blue) in the hinterland of the castella*.*

The number of 25 settlements is arbitrarily chosen as the available number of settlements in the MRP A in the entire study region equally divided over the number of forts. The exact number of settlements required to produce enough surplus to provide for the Roman military population is difficult to determine. For example, based on the analysis of Van Dinter *et al.* (2014, Table 14) of the Old Rhine region and looking only at arable farming in the MRP, approximately 11 settlements would be required to produce 50% of the cereals required to meet the military demand. De Kleijn (2018) contradicts this conclusion and finds that in the same region and time period the available settlements were not able to produce 50% of the required surplus. His analysis finds supply and demand values that roughly correspond to a required number of 26 settlements to meet these demands (De Kleijn 2018, 135), corresponding well with the value of 25 settlements chosen here.

Essentially, the hypothesis in Eq. 6.4 tests whether or not the sites that in previous archaeological research have been identified as potential 'local centres' functioning as intermediary sites in a dendritic system are indeed more 'central' in the distribution of goods than the *castella* themselves. However, the way this is measured results in a situation where it is likely that the 25 nearest settlements to the intermediary site are not the same as the 25 nearest settlements to the *castellum*. When considering the hypothesis as a question of which method of distribution is more efficient to get goods from any 25 rural settlements to the military population, regardless of where those 25 settlements are, this is not really a problem. Furthermore, irrespective of the outcome of the analyses of these hypotheses, it is likely that the reality is not as black-and-white and that these systems to some extent have co-existed. In a way this can also be measured, by calculating the amount of overlap between the respective subsidiary areas (consisting of the 25 nearest settlements) of a *castellum* and an intermediary site. The assumption here is then that if the overlap is 100% and the total path length of the intermediary site is shorter than that of the *castellum*, it more efficient when all settlements in the vicinity of the fort moved their goods through the intermediary sites to the *castellum*. In contrast, when there is no overlap, it may be argued that the *castellum* functioned as the 'central' gathering site in its own vicinity, while the intermediary site functioned as a gathering site for more distant settlements (Fig. 6.33).

Furthermore, it is also relevant to test whether or not these intermediary sites are actually 'central' enough in comparison to the average site in order to merit their designation as such a local centre in a dendritic settlement system. For this reason, the alternative hypothesis measure on the intermediary sites is also compared with the same measure applied to all other sites.

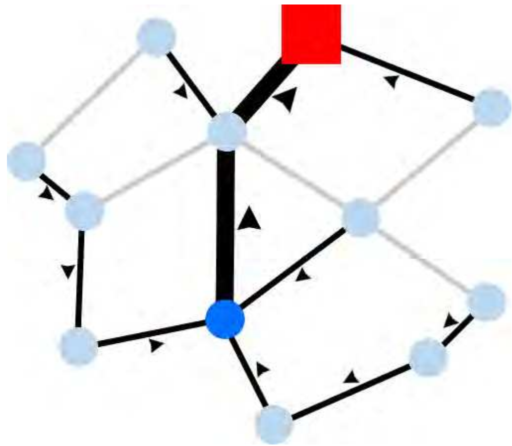


Figure 6.33. Schematic example of a situation where the castellum is the gathering site for its own vicinity (the three top-most sites), while the intermediary site functions as a gathering site for more distant settlements before the movement in bulk towards the castellum.

6.4.3.2 Results

In the previous section the approach was outlined to answer the general question: how were surplus produced goods moved from the rural to the military population? Two general hypotheses were composed: goods were being moved directly to the *castella* from each individual settlement (the null hypothesis), or goods were being moved through intermediary sites before moving towards the *castellum* (the alternative hypothesis). This section presents the bare results of this analysis, with a discussion of the results following in the next section.

The aforementioned hypotheses are tested through the comparison of total path length, which can be seen as the total travel time that any goods would have to move over the network. For the W20-network in the MRP A, these values are shown in Table 6.9. The overlap between the sets of 25 nearest settlements for each *castellum* that has at least one intermediary site associated with it are shown per intermediary site in Table 6.10. The values in Table 6.9 can be made more concrete by representing them in a graph. Figure 6.34 shows the total path length values for each *castellum* and the intermediary sites that are closest to it. To see how 'central' the intermediary sites are compared to other settlements in their vicinity, Figure 6.35 shows the comparison between total path length of each intermediary site with the average of all settlements that are nearest to the same *castellum*.

ID	Toponym	Nearest *castellum*	TPL	ID	Toponym	Nearest *castellum*	TPL
3132	Katwijk-Brittenburg (C)		5087.1	438	't Goy-Tuurdijk I (S)	Vechten	1262.4
4021	Valkenburg (C)		3814.4	448	Houten-Schalkwijkseweg 14 (L)	Vechten	919.2
4064	Leiden-Roomburg (C)		3356.5	455	Houten-Hofstad 16 (L)	Vechten	964.6
4022	Alphen aan den Rijn (C)		5024.5	468	Werkhoven-De Klaproos (L)	Vechten	1453.2
4066	Zwammerdam (C)		5954.0	476	Schalkwijk-Pothuizerweg II (S)	Vechten	1599.9
845	Woerden (C)		5118.3	500	Wijk bij Duurstede-De Horden (L+H)	Rijswijk	1625.3
781	Vleuten-De Meern (C)		1378.0	512	Houten-Doornkade (H)	Vechten	1124.8
505	Utrecht (C)		2233.2	513	Houten-Oud Wulfseweg (S)	Vechten	1071.3
502	Vechten (C)		1289.8	537	Kessel (V)	Rijswijk	3058.8
547	Rijswijk (C)		1834.2	619	Druten-Klepperhei (S)	Kesteren	2478.7
186	Maurik (C)		1913.9	674	Raayen-De Woerd (S)	Arnhem-M.	1501.1
839	Kesteren (C)		1677.4	725	Ewijk-De Grote Aalst (S)	Randwijk	2017.7
840	Randwijk (C)		2927.7	730	Beuningen-Reekstraat (S)	Randwijk	1990.7
687	Arnhem-Meinerswijk (C)		2456.0	731	Lent-Dorpsplein (S)	Loowaard	1713.8
1077	Loowaard (C)		2730.6	777	Beneden-Leeuwen-De Ret (S)	Kesteren	2363.8
763	Herwen-De Bijland (C)		4525.7	865	Cothen-Trechtweg (L)	Rijswijk	1515.6
110	Houten-Molenzoom (S)	Vechten	997.9	879	Hien-De Wuurdjes (S)	Randwijk	2718.6
111	Houten-Burg. Wallerweg (S)	Vechten	1035.3	1020	Heesbeen-Het Oude Maasje (S)	Rijswijk	5470.4
112	Houten-Tiellandt (H)	Vechten	1053.0	1041	Beuningen-Molenstraat (S)	Randwijk	1895.8
113	Houten-Wulven (S)	Vechten	1128.8	1056	Overasselt-Scheiwal (S)	Randwijk	2742.9
132	Echteld-Oude Weiden (S)	Kesteren	1271.7	1075	Middelaar-Witteweg (S)	Herwen-De Bijland	3561.5
134	Medel-Rotonde (S)	Kesteren	1477.1	1104	Millingen-Eversberg (S)	Herwen-De Bijland	3637.0
244	Tiel-Passewaaijse Hogeweg I (L+H)	Rijswijk	1836.2	1123	Ingen-De Poel (S)	Maurik	1748.5
315	Zennewijnen-Hoogekamp (S)	Rijswijk	2029.2	1124	Wijchen-Tienakker (S)	Randwijk	2284.6
372	Kesteren-De Woerd (S)	Kesteren	1587.5	2172	Lith (V)	Rijswijk	3032.3
422	Cothen-De Zemelen (L+S)	Rijswijk	1241.0	3099	Rijswijk-De Bult (S)	Valkenburg	2071.5
423	Cothen-Kapelleweg I (L)	Rijswijk	1229.1	3175	Voorburg (T)	Valkenburg	2797.5
426	Cothen-De Dom I (L)	Rijswijk	1413.6	4083	Naaldwijk-Middelbroekweg (S)	Valkenburg	2477.5
431	Cothen-Dwarsdijk I (L)	Rijswijk	1310.3	4092	Naaldwijk-Hoogwerf (S)	Valkenburg	3335.7

Table 6.9. Measurement of the total path length over the W20-network from the 25 nearest settlements (TPL) of the castella *along the Rhine (C) and the sites identified as potential 'local centres', including the town of Voorburg/*Forum Hadriani *(T),* vici *(V), stone-built rural settlements (S), sites with* horrea *(H) and large sites (L) as identified by Vos (2009).*

Site	Overlap	Site	Overlap	Site	Overlap
Valkenburg	**1**	**Rijswijk**	**1**	**Randwijk**	**1**
3099	0.12	244	0	725	0.23
3175	0.23	315	0	730	0.08
4083	0	422	0.35	879	0.62
4092	0	423	0.42	1041	0.12
Vechten	**1**	426	0.54	1056	0
110	0.65	431	0.46	1124	0
111	0.69	500	0.69	**Arnhem-M.**	**1**
112	0.69	537	0	674	0.73
113	0.73	865	0.65	**Loowaard**	**1**
438	0	1020	0	731	0.19
448	0.23	2172	0	**Herwen-De B.**	**1**
455	0.35	**Maurik**	**1**	1075	0.08
468	0.15	1123	0.58	1104	0.85
476	0	**Kesteren**	**1**		
512	0.81	132	0.38		
513	0.85	134	0.35		
		372	0.12		
		619	0		
		777	0.12		

Table 6.10. Overlap between the 25 nearest settlements for each intermediary site and the castellum *that is closest to them.*

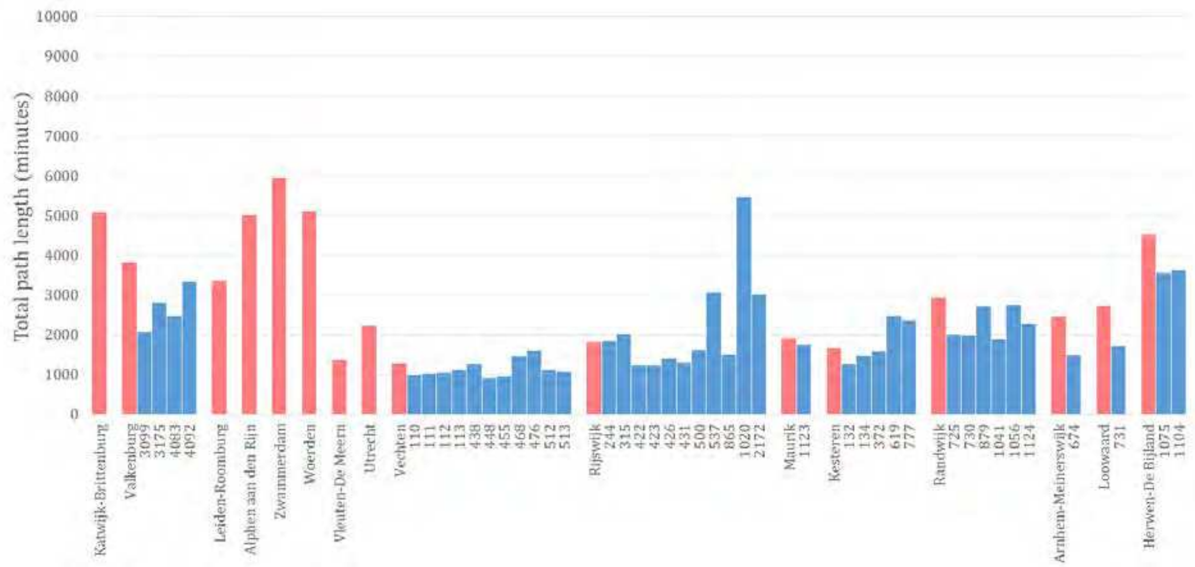


Figure 6.34. Comparison of $TPL_{castellum}$ (red colours) with $TPL_{intermediary}$ (blue colours) grouped by the nearest castellum *(TPL measured from the 25 nearest settlements).*

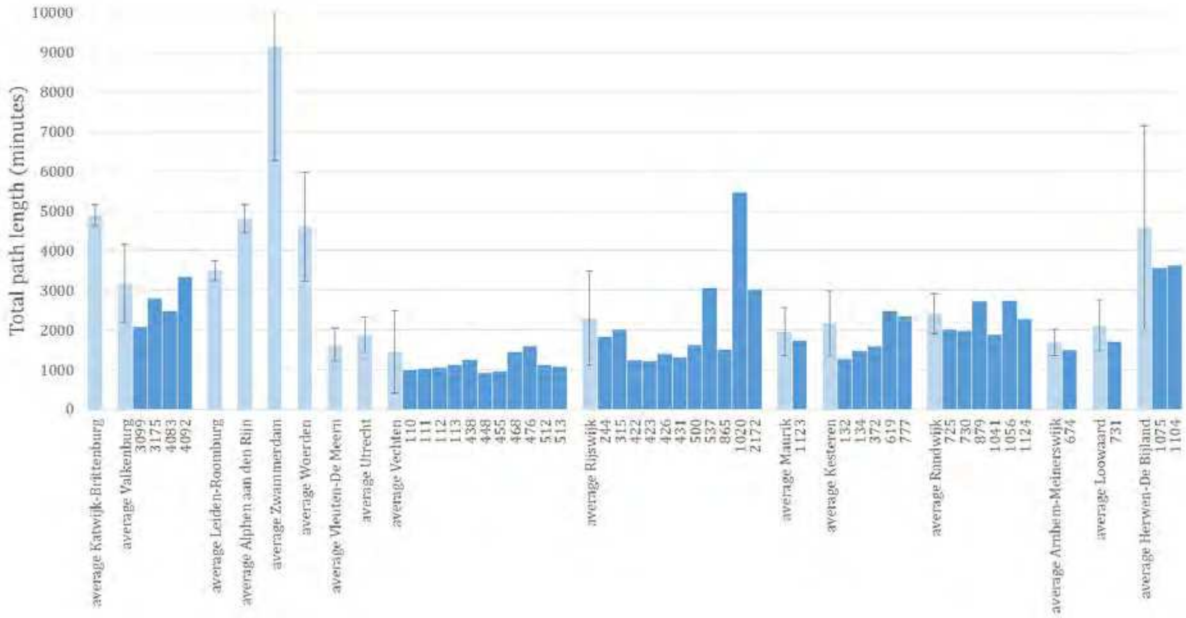


Figure 6.35. Comparison of the average of the TPL of all settlements near a castellum *(light blue colours, with the error bars representing one standard deviation) against* $TPL_{intermediary}$ *(dark blue colours) grouped by the nearest* castellum *(TPL measured from the 25 nearest settlements).*

It becomes clear that fairly little can be said about the western part of the study area (Katwijk-Brittenburg until Utrecht), since very few sites have been identified as potential 'local centres'. The only analysed intermediary sites in this area (including the town of Voorburg/*Forum Hadriani*) are found to be most proximate to the *castellum* of Valkenburg, although they are still quite distant and may also have served as intermediary sites for one of the other *castella* such as Katwijk-Brittenburg, Leiden-Roomburg and perhaps Alphen aan den Rijn. In any case, the total path length is shorter for the intermediary sites than it is for these *castella*, but only Voorburg/*Forum Hadriani* (site 3175) and Rijswijk-De Bult (site 3099) has a small amount of overlap of its subsidiary area with that of the *castellum*, while the other two sites do not (Fig. 6.36; see also Table 6.10). Compared to the average of all settlements, Voorburg and Naaldwijk-Middelbrugweg (site 4083) also have a lower total path length, but the difference is not greater than one standard deviation. The use of one standard deviation here does not imply that the difference is significant, since this is often only considered after a difference of two standard deviations (Cowles and Davis 1982). None of the potential intermediary sites fulfil this criterion, likely also as a result of the small set to which they are compared. However, the use of one standard deviation here does give an indication of the amount of variance in the set, and to what extent the intermediary site fits within that variance.

For the forts of Alphen aan den Rijn, Zwammerdam and Woerden it is difficult to draw conclusions on the basis of their total path length and that of any intermediary site, since their hinterland and potential supporting base is relatively small as a result of the narrow levee on which they are located and they have no intermediary sites that are closer to them than to any other *castellum*. De Bruin (2011) suggests that these forts were (partially) supplied by settlements further south, similar to the westernmost forts mentioned above. The *castella* of Vleuten-De Meern and Utrecht also have no intermediary sites that are closer to them than they are to any other fort, although since they are near the broader levees of the Kromme Rijn region it is possible that they may have shared their hinterland with the forts of Vechten and Rijswijk.

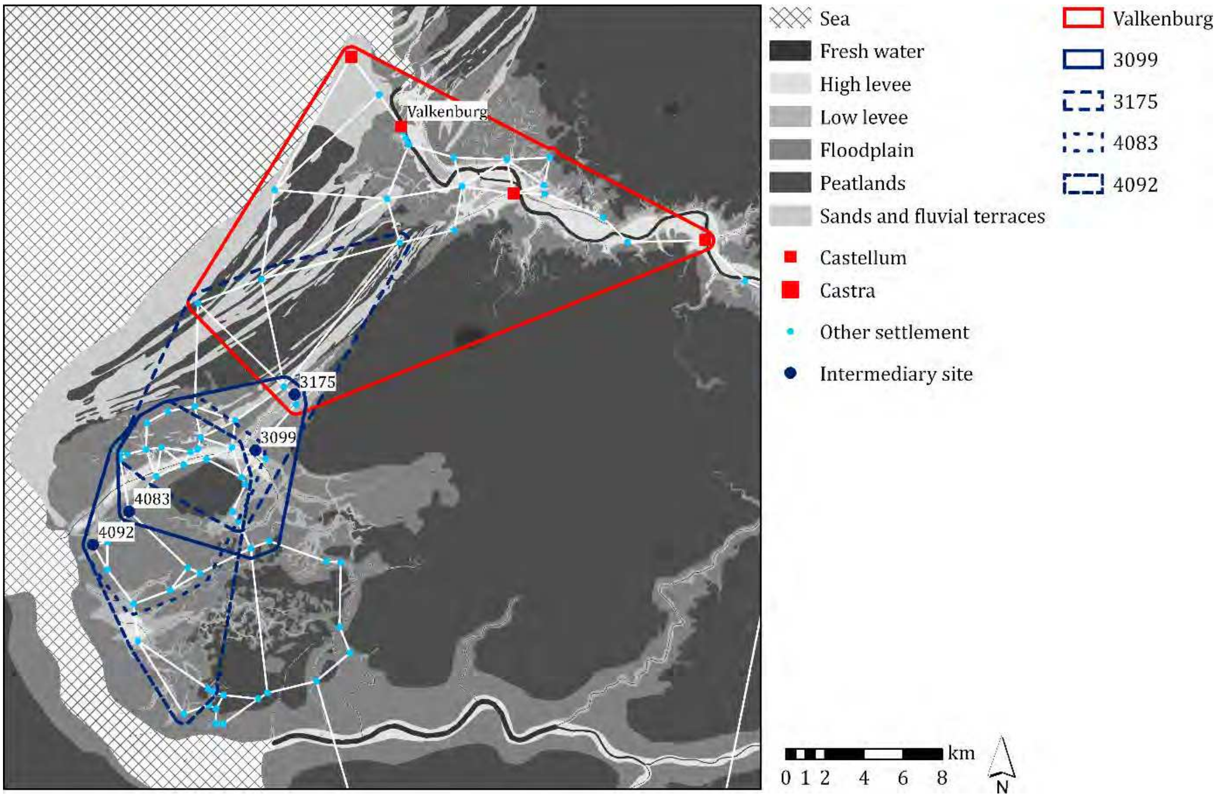


Fig. 6.36. Visualisation of the overlap between the 25 nearest settlements of the castellum *of Valkenburg and those of the intermediary sites closest to it.*

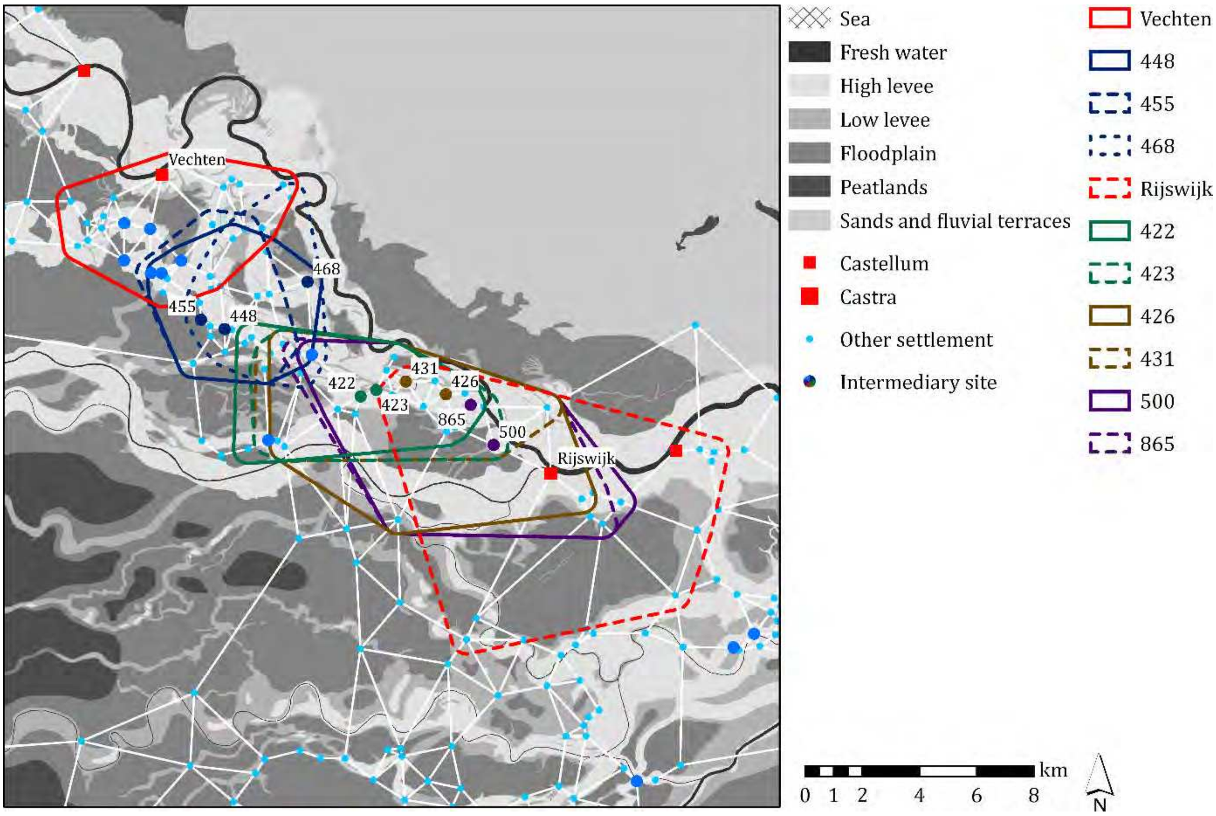


Fig. 6.37. Visualisation of the overlap between the 25 nearest settlements of the castella *of Vechten and Rijswijk and those of the intermediary sites categorised as large settlements by Vos (2009) closest to it. The outlines of other potential intermediary sites are omitted here to avoid cluttering the image.*

The forts of Vechten and Rijswijk have a notably larger amount of intermediary sites that are closer to them than to any other *castellum*. This is partly because the Kromme Rijn region of which these forts are a part was the subject of the study of Vos (2009), from which a number of additional (non-stone-built) settlements were selected as intermediary sites on the basis of being larger than the average rural settlement. However, it is also due to the fact that more stone-built rural settlements have been identified in the Kromme Rijn region. A number of intermediary sites are found to have a lower total path length than the *castella*, although this is not the case for all of them. What is particularly noteworthy is that the six intermediary sites that have a lower total path length than the *castellum* of Rijswijk are all sites that are categorised as large rural settlements, as defined by Vos (2009), and each one has between one-third and two-third overlap in subsidiary area with the *castellum* (Fig. 6.37). The other intermediary sites, among which are two *vici*, two stone-built rural settlements and a rural settlement with a *horreum*, actually have a higher total path length than the *castellum* of Rijswijk, but also have no overlap in subsidiary area with the fort. For the *castellum* of Vechten the majority of intermediary sites have a lower total path length, the lowest two of which have been categorised as large settlements by Vos (2009). There is a wide variation in the amount of overlap for the intermediary sites associated with the *castellum* of Vechten, with only two sites having zero overlap. Compared to the average of all settlements, none of the intermediary sites have a total path length that is lower than one standard deviation of the mean, although two sites near the *castellum* of Rijswijk come very close. Looking at the overlap visualisation (Fig. 6.37) in more detail, it can be seen that the sites that are categorised by Vos (2009) as large settlements are located between the two *castella* and have a number of settlements among their nearest 25 neighbours that are not among the 25 nearest neighbours of the forts. This explains why these sites have a lower total path length than the forts and some of the intermediary sites that are closer to the fort (particularly around Vechten), and thus shows why these sites in particular could have worked as relatively efficient intermediary sites. What can also be noticed in Figure 6.37 is that there is a large amount of overlap between the various potential intermediary sites, indicating that they may have functioned as an intermediary site for less (or even much less) than 25 other settlements.

The eastern part of the study area, between the forts of Maurik and Herwen-De Bijland, is characterised by broad expanses of densely settled levees and this is also visible in a consistent presence of intermediary sites. In most cases, the total path length of the intermediary site is lower than that of the closest *castellum*, the exceptions being two stone-built rural settlements nearest to the *castellum* of Kesteren. It is also generally lower than the average total path length of all settlements, although only one intermediary site has a difference that is larger than one standard deviation, namely Echteld-Oude Weiden (site 132) near the *castellum* of Kesteren. Some more sites are just below one standard deviation from the mean. The amount of overlap between the subsidiary areas of the intermediate sites and their nearest *castella* is varying, with some sites having zero overlap, and some sites such as Raayen-De Woerd (site 674) near the fort of Arnhem-Meinerswijk and Millingen-Eversberg (site 1104) near Herwen-De Bijland having substantial amounts of overlap. Similar to the intermediary sites near Vechten and Rijswijk, the intermediary sites with the lowest total path length are often ones that have are more or less halfway between two forts yet have little overlap with the forts in their 25 nearest neighbours (e.g. site 132; Fig. 6.38).

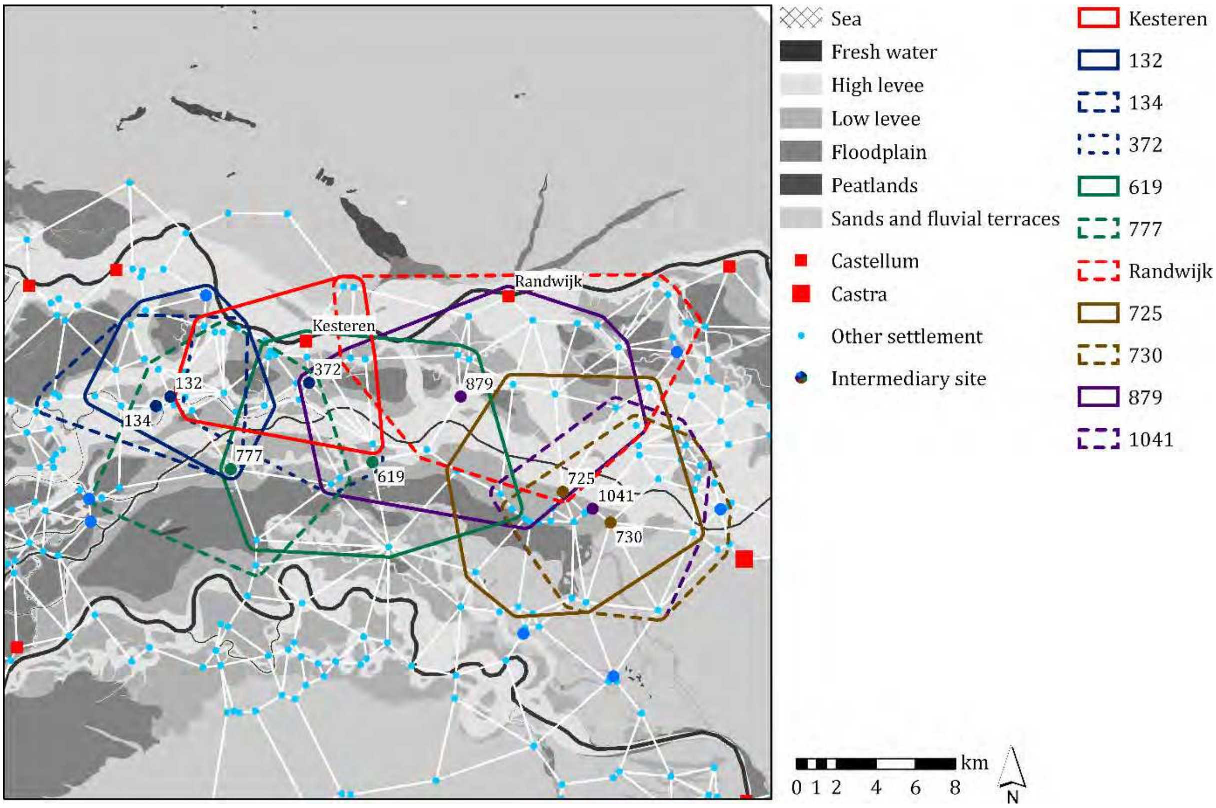


Fig. 6.38. Visualisation of the overlap between the 25 nearest settlements of the castella *of Kesteren and Randwijk and those of the intermediary sites closest to it. The outlines of other potential intermediary sites are omitted here to avoid cluttering the image.*

6.4.3.3 Discussion: the flow of goods from the rural to the military population

The heart of the question is what the results presented in the previous section mean for our hypotheses surrounding the distribution of surplus goods from the rural population to the military population. The discussion of this study will be separated between a treatise of this topic in the current section, and some comments on the applied methodology for this research question in the next section, in order to avoid condensing too many arguments into one segment.

For the *castella* in the western part of the study area, it was shown that very few intermediary sites have been identified. The only ones present, the town of Voorburg/*Forum Hadriani* and two stone-built rural settlements, are in the westernmost part and were found to be closest to the *castellum* of Valkenburg, although they are relatively far removed still. Only Voorburg and Rijswijk-De Bult (site 3099) have some overlap of their subsidiary areas (the 25 nearest settlements) with that of the *castellum* of Valkenburg. The three intermediary sites are located near the Meuse estuary and the Gantel system that enters the Meuse from the north, where besides transport over land (which is modelled in this network) goods could also possibly have been moved up the *Fossa Corbulonis* to the *castellum* of Leiden-Roomburg. They are all found to have a lower total path length than the *castella* themselves, which shows that they could possibly have functioned as gathering sites for their local vicinity prior to the movement of goods towards the *castellum*. This is not solely the case for Valkenburg, as the intermediary sites also have a lower total path length to the *castella* of Katwijk-Brittenburg, Leiden-Roomburg and Alphen aan den Rijn compared to the total path length to reach the *castella* directly. For the westernmost three forts and perhaps even for Alphen aan den Rijn, it can thus be stated that the alternative hypothesis is more likely than the null hypothesis, i.e. it is more efficient to move any surplus goods through more centrally located gathering sites compared to moving the goods directly to the *castella*.

However, the fact that subsidiary areas of the intermediary sites (almost) do not overlap with those of the *castella* shows that it is possible for the *castella* to have functioned as gathering sites for the settlements in their direct vicinity, resulting in a situation where both systems of distribution could have been present concurrently.

The *castella* that are located along the narrowest section of the Rhine channel belt, namely Alphen aan den Rijn, Zwammerdam and Woerden, have no intermediary sites that are closer to them than to any other settlement. Furthermore, there are so few settlements in their vicinity in general that their total path length to their nearest 25 settlements is much larger than that of the other *castella*. It is therefore imaginable that these forts only relied on their direct hinterland to a limited extent, in which they functioned as the direct gathering site independently, but were dependent on regional provisioning lines for the bulk of their requirements, including transport over the Rhine from the central and eastern parts of the Rhine-Meuse delta.

The *castella* of Vleuten-De Meern and Utrecht are located just outside of the Kromme Rijn region in the heart of the Rhine-Meuse delta and to some extent can be expected to have relied on that hinterland for their provisioning. This is also reflected in their lower total path length, indicative of better access to a more densely settled area, certainly compared to the three forts neighbouring to the west. Similar to the western forts, they may thus have functioned as gathering sites for settlements in their immediate vicinity, while at the same time relying on more distant intermediary sites, most likely in the Kromme Rijn region, to supplement their requirements.

The Kromme Rijn region has a relatively dense settlement pattern, and that is reflected in the low total path length of the *castella* of Vechten and Rijswijk, located on the edges of this region. It was for this region in particular that Vos (2009) hypothesised that there are a number of settlements that function as intermediary sites in a hierarchic system, including stone-built rural settlements and some rural settlements that are larger than average, the latter category of which are not distinguished as intermediary sites outside the Kromme Rijn region due to the simple fact that this attribute is not uniformly specified in the archaeological site database (and difficult to substantiate when the archaeological evidence is sparse). For the *castellum* of Rijswijk the associated intermediary sites that have a lower total path length are all part of this category of large rural settlements (one of which is also stone-built), whereas two smaller stone-built rural settlements and two *vici* (Kessel and Lith) actually have a higher total path length than the *castellum* itself. However, this higher total path length is also a result of them being generally further away than the other intermediary sites and in an area with lower settlement density, e.g. on or near the levees of the Meuse in the south of the research area. This is also reflected in the amount of overlap of the subsidiary areas of these sites with those of the *castella* being fairly low to non-existent. The two intermediary sites with the lowest total path length near the *castellum* of Vechten are similarly identified as large rural settlements by Vos (2009). All of these large rural settlements have some overlap in their subsidiary area with that of the *castella*, ranging between 0.23 and 0.69, and are generally located in the area between the two forts, covering some settlements that are outside the subsidiary areas of the forts. Some small stone-built rural settlements near the fort of Vechten have up to 0.85 overlap with a lower total path length than the *castellum*, albeit slightly higher than that of the large rural settlements. It can be stated that the alternative hypothesis is more likely than the null hypothesis: it would have been more efficient to move surplus goods through a number of intermediary sites, particularly those identified as large settlements by Vos (2009), than it would be to move them directly to the *castella*, at least as far as the Kromme Rijn region and its direct surroundings are concerned. Some more distant settlements that were identified as intermediary sites do not fulfil this role efficiently (i.e. direct transport to the fort would be more efficient), which leads to a conclusion that they may not have been intermediary sites in local transport networks at all, or they may have functioned as such in a different context (e.g. as part of a Meuse-based transport network over water).

From Maurik to Herwen-De Bijland, all forts have at least one intermediary site that is closer to them than to any other *castellum*. The *castella* of Maurik, Randwijk, Arnhem-Meinerswijk and Herwen-De Bijland all have an intermediary site that have at least a 50% overlap with their subsidiary areas, and all of those intermediary sites have a lower total path length from its 25 nearest settlements than the *castella* themselves. In general they are also quite well below the average total path length of all settlements (around one standard deviation below the mean). Some sites that are more distant (reflected in low to zero overlap) also have a lower total path length than the *castella*, both for the aforementioned forts, as well as for the *castella* of Kesteren and Loowaard that have no nearby intermediary sites. It can thus be concluded that the alternative hypothesis for these *castella* and intermediary sites is more likely than the null hypothesis: it would have been more efficient to move goods through the intermediary sites than to the *castella* directly. This is true both for the intermediary sites that are near the *castellum* and for the ones that serve more distant areas.

When comparing the total path length of the intermediary sites against the average total path length of all settlements near the same *castellum*, it becomes clear that although they generally have lower values than average, it is quite rare for the intermediary site to outperform the average by more than one standard deviation. This only occurred in one instance (site 132, Echteld-Oude Weiden near the *castellum* of Kesteren), with a number of other intermediary sites being close to one standard deviation below the mean. A conclusion that can be drawn from this is that although it is possible that these settlements have become intermediary sites through a beneficial location in potential local distribution networks, the measurements of total path length are not convincing enough to state that it is the only reason why these settlements could have become intermediary sites where others could not. Possible explanations could be that there are other (not transport-related) factors that determined that these particular settlements became intermediary sites (e.g. demographic or political), or that these settlements were already important in local transport networks prior to the MRP A (the period under study here), which is a question discussed further in section 6.4.4.

6.4.3.4 Discussion: the applied methodology

The previous section discussed the question of which method of distribution of goods would be more efficient, through the evaluation of a null hypothesis where all goods moved directly from the rural settlements to the *castellum* and an alternative hypothesis in which goods moved firstly through an intermediary site. One of the questions that can be asked of the applied methodology is what would change if the total path length values for *castella* and intermediary sites would only be calculated for the same subsidiary area (as opposed to a separate set of 25 nearest neighbours for each fort and intermediary site as was used now). One imaginable experiment would be to calculate total path length values twice: once for the *castellum* and the intermediary site in relation to the subsidiary area of the *castellum*, and once for the *castellum* and the intermediary site in relation to the subsidiary area of the intermediary site. The result would in most instances be that the intermediary site is a more efficient gathering point for its subsidiary area than the *castellum* would be for the same area, and vice versa, especially when the amount of overlap between the subsidiary areas is low.

However, in this light it is most interesting to evaluate what would happen when the amount of overlap is high, which is the case for some settlements in the Kromme Rijn region and some of the eastern *castella*. For example, when calculating the total path length of site 512 (Houten-

Doornkade, with an overlap of 0.81) for the 25 settlements that are nearest to the *castellum* of Vechten (as opposed to the 25 nearest to itself), the total path length is found to be 1209.5 minutes. That is about 7.5% higher than the total path length of the 25 settlements nearest to itself, but still lower than the total path length of the *castellum* (1289.8 minutes). Similar results are found for other intermediary sites with high overlap in subsidiary areas. The conclusion that can be drawn from this is that the intermediary sites in the direct vicinity of a *castellum* (resulting in a high overlap of the 25 nearest settlements) can be efficient gathering points for the movement of goods from the rural settlements to the *castella*, independent of the choice of 25 nearest settlements (i.e. nearest to itself or nearest to the fort).

One limitation in the methodology is the limited specification of sites that are singled out in this study. Most intermediary sites were chosen because they are identified as a stone-built rural settlement in the archaeological site database, and some in the Kromme Rijn region were selected because they have been identified by Vos (2009) as potential intermediary sites. However, there may be potential intermediary sites overlooked in this simplification.

Furthermore, the analysis was only done with supplying the military population in the *castella* along the Rhine in mind, but Roman military were stationed at other places in the Rhine-Meuse delta as well (e.g. the *castra* of Nijmegen or the mini-*castellum* of Ockenburgh), and any supply to other non-producing populations (e.g. the civilian population of Nijmegen and Voorburg) has so far not been explicitly considered and evaluated. While the analysis will not be repeated in full, Table 6.11 shows a comparison of the total path length of the *civitas* capitals compared to the nearest intermediary sites. For Voorburg, two of the potential intermediary sites have a lower total path length and are thus deemed more efficient as an intermediary station for the flow of goods towards Voorburg compared to moving goods directly. This was also the case when evaluating these intermediary sites in relation to the fort of Valkenburg, with which they have no overlap in their 25 nearest neighbours. The reason why these two potential intermediary sites function efficiently for the transport of goods not only for distant destinations (Valkenburg and other forts) but also for nearby destinations (Voorburg) is that they are more centrally located in relation to the other rural settlements, compared to Voorburg and Naaldwijk-Hoogwerf (site 4092), which are quite peripheral in the concentration of settlements in the Meuse estuary region.

When looking at Nijmegen, it becomes very apparent that Nijmegen itself was relatively centrally located for other settlements. Only two of the potential intermediary sites fulfil a role where they are more efficient for the transport of goods compared to moving goods directly to Nijmegen. Of these two, site 731 (Lent-Dorpsplein) is very close and has an overlap of 0.85 in its subsidiary area with that of Nijmegen, while site 674 (Raayen-De Woerd) is further away (in the vicinity of the *castellum* of Arnhem-Meinerswijk) and only has an overlap of 0.23. For both of these intermediary sites the reason that they are more efficient for transport is that they are more accessible for the area of high settlement density just north of Nijmegen. The other intermediary sites are located west, southwest or east of Nijmegen in areas of comparatively lower settlement density. It can thus be stated that for the hinterland of Nijmegen south of the Waal river, it would be more efficient to move goods directly to Nijmegen than through any intermediary site, while for the area north of the Waal river an intermediary site would be more efficient.

As a final methodological consideration, this analysis was performed using the Gabriel graph as a network structure, as it was found to be the best representation of a local transport network in Groenhuijzen and Verhagen (2017) and section 6.2. However, in principal the same analysis can also be applied to other network structures. This has not been carried out in full and will thus not be discussed here in great detail, but a preliminary analysis shows that proximal point networks with a high number of neighbours and the Delaunay triangulation give similar results, indicating that travel time over the network is not very different, and the changes are spread nearly evenly so that the relative difference between the *castella* and intermediary sites remain the same. This is not the case for instance for proximal point networks with a low number of neighbours or maximum distance networks, since these have the problem that not all sites are part of a single component, so that it is impossible for many sites to calculate the total path length to a number of nearest settlements.

ID	Toponym	Distance to city	TPL	Overlap
3175	**Voorburg**	**0**	**2522.6**	**1**
3099	Rijswijk-De Bult	68.8	1796.6	0.88
4083	Naaldwijk-Middelbroekweg	176.3	2202.6	0.62
4092	Naaldwijk-Hoogwerf	225.9	3060.8	0.50
841	**Nijmegen**	**0**	**1699.2**	**1**
674	Raayen-De Woerd	160.7	1561.5	0.23
725	Ewijk-De Grote Aalst	115.0	1966.0	0.31
730	Beuningen-Reekstraat	67.6	1844.2	0.62
731	Lent-Dorpsplein	32.4	1532.7	0.85
1041	Beuningen-Molenstraat	85.0	1784.2	0.54
1056	Overasselt-Scheiwal	144.8	2560.3	0.15
1104	Millingen-Eversberg	244.3	3816.6	0.19
1124	Wijchen-Tienakker	199.0	2181.3	0.08

*Table 6.11. Measurement of the total path length over the W20-network from the 25 nearest settlements (*TPL*) of the* civitas *capitals and nearby sites identified as potential 'local centres' (all of which are classified as stone-built rural settlements). This includes some intermediary sites that are actually closer to a* castellum *than they are to the cities.*

6.4.3.5 Conclusion

In this study the distribution of surplus goods from the rural population to the military population was studied using network concepts, by designing and evaluating two contrasting hypotheses: a null hypothesis in which all goods are moved directly to the nearest *castellum*, and an alternative hypothesis where goods are moved firstly to an intermediary site and then in bulk to a *castellum*. A number of potential intermediary sites were identified on the basis of the criteria set by Vos (2009), who proposed a dendritic hierarchic settlement system in his study of the Kromme Rijn region.

It was found that for the central and eastern parts of the Rhine-Meuse delta, the alternative hypothesis is more likely than the null hypothesis: it would have been more efficient to move goods to a more central gathering point before being transported in bulk to a *castellum*. Most of these *castella* have intermediary sites in their direct vicinity as well as further away, so that all goods can be distributed through this system. Exceptions here are the *castella* of Loowaard and Kesteren, that do not have intermediary sites very closely associated with them, indicating that they either may have functioned as a local gathering site for their direct vicinity, or that another intermediary site is unidentified.

Along the western part of the Rhine, some *castella* have no intermediary sites associated with them at all, which can be interpreted as them functioning as their own gathering points for the few settlements that are on the narrow levee in their environment, as well as them having to rely on more distant sources. The westernmost *castella* similarly have no intermediary sites in their direct vicinity, but do have access to some intermediary sites near the Meuse estuary, for example over the *Fossa Corbulonis*. This can be interpreted as a dual system, where settlements that are near the *castellum* move their goods directly there, whereas more distant settlements collect their goods at these intermediary sites.

Of course, it is realistic to assume that to some degree all *castella* could have functioned as local gathering sites for settlements that are nearby, but by expressing the problem in two contrasting hypotheses it was found that it would have been more efficient for the majority of movement of goods to occur through intermediary sites. Whether the sites identified as intermediary sites were all in fact intermediary sites remains an open question, as it was found that although they generally perform better on the evaluated criterion than the average settlement, they do not exceed that average by great margins. An explanation for this could be that these settlements owe their higher status in the proposed hierarchic system in part through their position in distribution networks, but also due to factors unrelated to transport.

Unaddressed in this study is the movement of goods in the opposite direction, such as the distribution of imported pottery. However, in essence the hypotheses tested in this study can operate in the same way in a scenario of distribution from the *castella* towards the rural settlements. The result would thus be that it would be more efficient for the majority of the distribution to occur through intermediary sites, as the total path length of movement from the *castella* to the rural settlements through intermediary sites is lower than the total path length of movement from the *castella* to the rural settlements directly. This approach would thus be a valuable opportunity for future research, as besides testing these hypotheses through network analysis, it can also be more easily validated through a comparison with the archaeological evidence.

6.4.4 The position of stone-built rural settlements

6.4.4.1 Methodology

A secondary question that has been posed in section 6.1.2 is the role of stone-built rural settlements in networks of transport. This question has been given more weight after the conclusion in section 6.4.3.5 that some potential intermediary sites identified in archaeological research (many of which are stone-built rural settlements) do not stand out among other settlements in terms of total path length to the 25 nearest settlements, the metric used there to compare two hypotheses on the distribution of goods from the rural to the military population.

What would be interesting to know is thus if an advantageous position of these settlements in networks of transport at some point in time may have led them to grow in importance and become stone-built. The implication is here that these settlements have had some role in transport networks (especially in the pre-stone-built phase, i.e. the Early Roman Period) that sets them apart from other rural settlements. One network measure through which this can be evaluated is betweenness centrality, which is essentially a representation of the amount of control that a site has over movements in the network. The question can thus be stated more explicitly as: is there a noticeable/significant difference in betweenness centrality for the stone-built settlements compared to other settlements? This question will be explored in the following results and discussion sections. It will make use of the datasets already introduced in section 6.4.2.

6.4.4.2 Results

This section will provide results derived through network analysis regarding the question alluded to earlier in section 6.1.2 and stated more explicitly in section 6.4.4.1: do stone-built rural settlements have a special role in transport networks, recognisable through a noticeable/significant difference in betweenness centrality (C_B) for the stone-built settlements compared to other settlements?

The most straightforward first step is to measure the average C_B for the stone-built rural settlements and compare that to the average C_B of all settlements. The results of this procedure are listed in Table 6.12 for the W20-network and Table 6.13 for the OC-network, and particular for the W20-network of the MRP A an impression of the spatial distribution of C_B is given in Figure 6.39.

Period		All	Stone-built	Difference	p-value
LIA	$\overline{C_B}$	0.0385	0.0575	+0.0190	0.2663
	n	284	18*		
	σ	0.0539	0.0691		
ERP A	$\overline{C_B}$	0.0352	0.0447	+0.0096	0.5355
	n	287	20*		
	σ	0.0568	0.0731		
ERP B	$\overline{C_B}$	0.0349	0.0366	+0.0017	0.8772
	n	352	22*		
	σ	0.0531	0.0585		
MRP A	$\overline{C_B}$	0.0299	0.0228	-0.0071	0.6909
	n	525	28		
	σ	0.0475	0.0342		
MRP B	$\overline{C_B}$	0.0285	0.0167	-0.0118	0.0644
	n	587	33		
	σ	0.0479	0.0178		
LRP A	$\overline{C_B}$	0.0348	0.0302	-0.0047	0.5833
	n	335	23		
	σ	0.0541	0.0393		
LRP B	$\overline{C_B}$	0.0327	0.0240	-0.0087	0.2734
	n	367	23		
	σ	0.0526	0.0390		

*Table 6.12. Comparison between average betweenness centrality ($\overline{C_B}$) values of all settlements versus stone-built rural settlements in the W20-network, with the number of sites (n) and standard deviation (σ). The final column shows the results of a two-tailed unequal variance Student's T-test on H0: ($\overline{C_{B\,all}} = \overline{C_{B\,stone-built}}$). *Stone-built rural settlements were regular post-built rural settlements at least during the LIA-ERP B interval, and only became stone-built afterwards.*

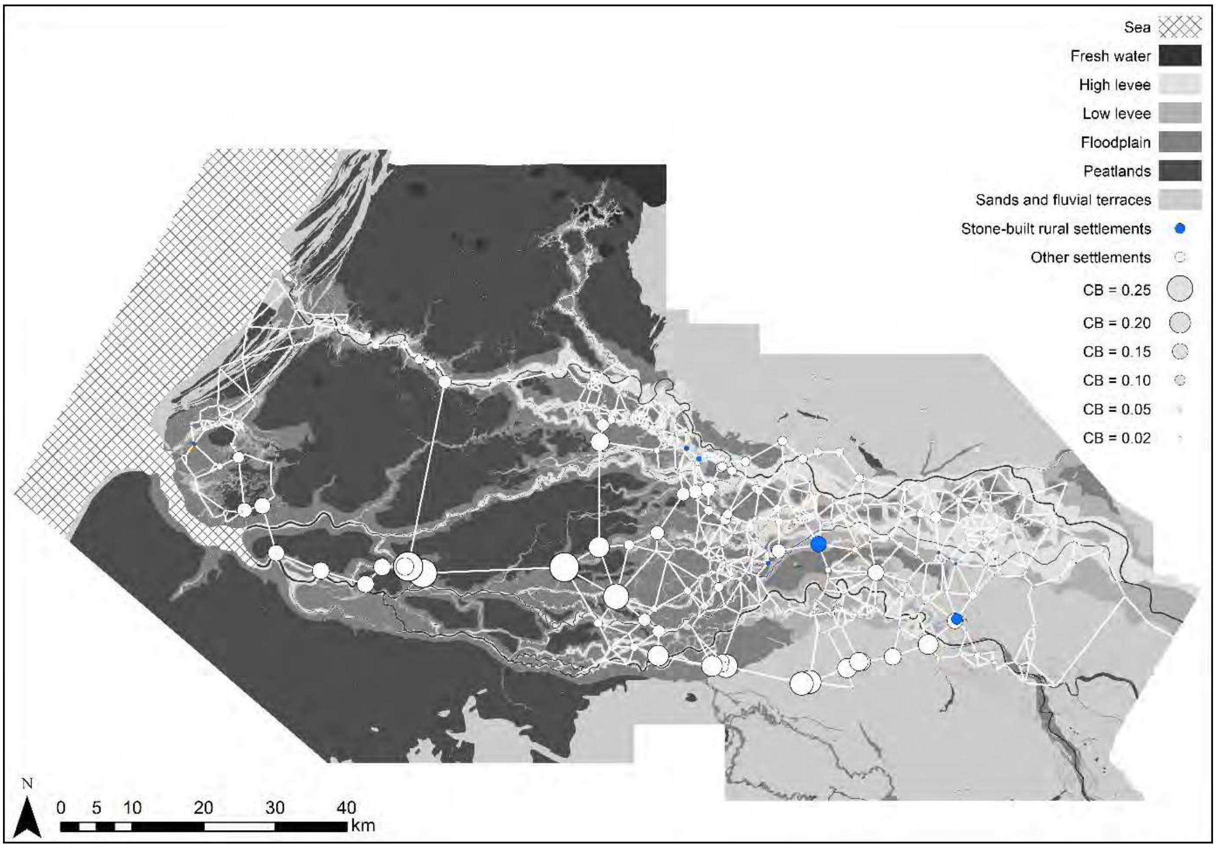


Figure 6.39. C_B measurements of stone-built rural settlements and all other settlements.

Period		**All**	**Stone-built**	**Difference**	***p*-value**
LIA	$\overline{C_B}$	0.0354	0.0463	+0.0108	0.3861
	n	284	18*		
	σ	0.0499	0.0503		
ERP A	$\overline{C_B}$	0.0339	0.0486	+0.0147	0.2997
	n	286	20*		
	σ	0.0507	0.0623		
ERP B	$\overline{C_B}$	0.0296	0.0387	+0.0091	0.4683
	n	352	22*		
	σ	0.0516	0.0546		
MRP A	$\overline{C_B}$	0.0233	0.0195	-0.0038	0.8409
	n	524	28		
	σ	0.0404	0.0300		
MRP B	$\overline{C_B}$	0.0227	0.0165	-0.0062	0.2763
	n	586	33		
	σ	0.0385	0.0223		
LRP A	$\overline{C_B}$	0.0326	0.0285	-0.0042	0.5809
	n	335	23		
	σ	0.0512	0.0325		
LRP B	$\overline{C_B}$	0.0311	0.0325	0.0014	0.8640
	n	367	23		
	σ	0.0539	0.0552		

*Table 6.13. Comparison between average betweenness centrality ($\overline{C_B}$) values of all settlements versus stone-built rural settlements in the OC-network, with the number of sites (n) and standard deviation (σ). The final column shows the results of a two-tailed unequal variance Student's T-test on H0: ($\overline{C_{B\ all}} = \overline{C_{B\ stone-built}}$). *Stone-built rural settlements were regular post-built rural settlements at least during the LIA-ERP B interval, and only became stone-built afterwards.*

From the calculated p-values through a Student's T-test it can be deduced that the difference in C_B of the two sets is not statistically significant. The only time when it approaches significance is during the MRP B in the W20-network, where a p-value of 0.0790 was measured. However, the difference here is actually not in favour of stone-built settlements: on average they have a lower C_B than the complete settlement dataset. Looking at individual stone-built settlements rather than the entire group, rarely more than three exceed the average C_B by more than one standard deviation during any given time period.

However, this is only an indication of how the stone-built settlements fare compared against the entire dataset, and Figure 6.39 shows that the majority of settlements with a high C_B are located where settlement density is lowest, and that is not where stone-built rural settlements are usually found. This can be seen as a bottleneck effect, which is further discussed in the following section 6.4.4.3. Because of these heterogeneous C_B values that are dependent on settlement density, it may be better to compare stone-built settlements against their direct environment only. For example, we can compare C_B of stone-built settlements with that of the ten nearest settlements (in terms of modelled direct travel time, so that the definition of nearest is not dependent on the choice of network structure). The results for the W20-network are shown in Table 6.14.

The results of Table 6.14 show that especially for the LIA-MRP B interval, roughly a third of the stone-built rural settlements exceed the average C_B of the ten nearest settlements by more than one standard deviation. While one standard deviation is not a measure of significance, it gives an indication of how different these sites are from the average, which may help explain why some settlements have become stone-built (further discussed in the next section). Some results may even be seen as significantly different, namely those that deviate more than two standard deviations from the average (cf. Cowles and Davis 1982). Not a single one of the settlements that outperform the average by more than one standard deviation do so in the LRP exclusively; any settlement that has a C_B that exceeds the mean by more than one standard deviation during the LRP already did that at least once before in one of the preceding time periods. Furthermore, there are only three instances where this status is achieved in the MRP at the latest. The remaining 14 settlements that at any time exceed the average C_B by more than one standard deviation already did that for the first time in the LIA-ERP B interval.

Site ID	Toponym	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
110	Houten-Molenzoom				-0.04	-0.05		
111	Houten-Burg. Wallerweg	-0.63	-0.69	-0.83	-0.76	-0.76	-0.54	-0.73
113	Houten-Wulven	0.87	0.50	-0.16	0.38	0.45	-0.70	-0.09
132	Echteld-Oude Weiden		0.11	0.00	-0.13	-0.15	-0.19	0.21
134	Medel-Rotonde	0.48	-0.57	-0.48	-0.41	-0.82	-0.55	-1.08
315	Zennewijnen-Hoogekamp		-0.12	-0.70	0.00	-0.03	-0.09	0.29
372	Kesteren-De Woerd	2.68	-0.10	1.27	-0.83	-0.88	-0.55	-0.26
422	Cothen-De Zemelen	1.24	-0.41	-0.51	2.00	1.73	-0.24	0.42
432	Werkhoven-Zure Maat	-1.62						
438	't Goy-Tuurdijk I	-0.19	1.17	1.46	1.87	1.32	1.07	0.67
476	Schalkwijk-Pothuizerweg II	2.61	-0.50	-0.44	-0.28	-0.57	0.42	1.22
513	Houten-Oud Wulfseweg	1.10	-0.29	-0.58	0.01	0.45	0.38	0.68
613	Winssen-Oude Veerhuis					-0.42		
619	Druten-Klepperhei	-0.13	3.67	3.68	-0.37	-0.44	0.06	-0.25
620	Deest-Grotestraat					1.12		
661	Hernen-De Wijnakker	0.74				0.82		
674	Raayen-De Woerd	1.48	1.19	-0.55	1.42	0.56	1.47	4.07
725	Ewijk-De Grote Aalst	5.67	-0.31	0.53	2.09	2.99	-0.23	-0.33
730	Beuningen-Reekstraat	-0.03			1.35	1.31	0.81	0.89
731	Lent-Dorpsplein	-1.85	-0.38	-0.05	0.22	1.15	-0.46	-0.27
777	Beneden-Leeuwen-De Ret	1.39	55.89	14.16	7.08	2.12	3.20	6.28
879	Hien-De Wuurdjes				-0.87	-0.75		
1020	Heesbeen-Het Oude Maasje				-1.06	-0.93		-0.95
1041	Beuningen-Molenstraat		-0.99	1.26	-0.54	0.13	-0.64	-0.55
1056	Overasselt-Scheiwal				1.42	1.35	0.99	
1075	Middelaar-Witteweg			-0.84	-1.28	-0.04	-1.09	-0.86
1076	Plasmolen-Kloosterberg					-0.02		
1104	Millingen-Eversberg				-1.11	-1.14		
1123	Ingen-De Poel	0.25	1.99	2.10	-0.39	0.41	2.20	0.91
1124	Wijchen-Tienakker		0.84	1.18	-1.50	-0.80	0.34	-1.66
3092	Poeldijk-Wateringseweg					0.27		
3099	Rijswijk-De Bult			-0.01	-0.42	0.73		
4083	Naaldwijk-Middelbroekweg		-0.90	1.00	5.23	0.37	1.50	-0.60
4092	Naaldwijk-Hoogwerf	-0.60	-0.57	-1.08	-0.83	-1.37	-0.66	-0.80

	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
n	18*	20*	22*	28	33	23	23
n with $C_B \geq \overline{C_{B\,10\,nn}} + \sigma_{10\,nn}$	7	5	8	8	8	5	3
n with $C_B \geq \overline{C_{B\,10\,nn}} + \sigma_{10\,nn}$ (%)	38.9	25	36.4	28.6	24.2	21.7	13.0

*Table 6.14. Deviation of the C_B of stone-built rural settlements in the W20-network from the average for the ten nearest settlements ($C_{B\,10\,nn}$), expressed in terms of the standard deviation of that set ($\sigma_{10\,nn}$). Highlighted values are those who deviate by a value larger than 1 σ (dark green = +2 σ; light green = +1 σ; yellow = -1 σ). *Stone-built rural settlements were regular post-built rural settlements at least during the LIA-ERP B interval, and only became stone-built afterwards.*

The OC-network has comparable results, with some differences resulting in just slightly lower C_B values for the stone-built rural settlements and consequentially some sites dropping just below one standard deviation difference, as indicated in the same analysis in Table 6.15.

Site ID	Toponym	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
110	Houten-Molenzoom				-0.04	-0.04		
111	Houten-Burg. Wallerweg	-0.42	-0.63	-0.83	-0.81	-0.76	-0.54	-0.73
113	Houten-Wulven	0.87	0.50	-0.16	0.74	0.83	-0.70	-0.09
132	Echteld-Oude Weiden		0.11	0.00	-0.13	-0.15	-0.19	0.21
134	Medel-Rotonde	0.56	-0.57	-0.48	-0.41	-0.82	-0.55	-1.08
315	Zennewijnen-Hoogekamp		-0.15	-0.70	0.00	-0.03	-0.09	0.29
372	Kesteren-De Woerd	1.99	-0.35	-0.06	-0.83	-0.88	-0.54	-0.32
422	Cothen-De Zemelen	1.24	-0.41	-0.51	2.00	1.73	-0.24	0.42
432	Werkhoven-Zure Maat	-1.56						
438	't Goy-Tuurdijk I	-0.19	1.17	1.46	1.87	1.37	1.07	0.63
476	Schalkwijk-Pothuizerweg II	2.57	-0.50	-0.44	-0.28	-0.58	0.43	1.22
513	Houten-Oud Wulfseweg	1.10	-0.18	-0.62	0.01	0.33	0.52	1.01
613	Winssen-Oude Veerhuis					-0.74		
619	Druten-Klepperhei	-0.30	1.61	1.61	-0.55	-0.12	-0.33	-0.45
620	Deest-Grotestraat					1.12		
661	Hernen-De Wijnakker	0.54				0.60		
674	Raayen-De Woerd	0.33	1.16	-0.46	1.42	0.56	0.34	3.11
725	Ewijk-De Grote Aalst	5.67	-0.31	0.49	1.17	3.04	-0.28	-0.35
730	Beuningen-Reekstraat	-0.17			0.55	0.35	0.84	0.90
731	Lent-Dorpsplein	-1.65	-0.53	-0.11	0.22	1.15	-0.63	-0.44
777	Beneden-Leeuwen-De Ret	1.39	2.21	3.59	7.76	2.10	10.51	5.51
879	Hien-De Wuurdjes				-0.92	-0.62		
1020	Heesbeen-Het Oude Maasje				-1.05	-0.83		-0.95
1041	Beuningen-Molenstraat		-1.11	1.00	-0.61	0.09	-0.77	-0.69
1056	Overasselt-Scheiwal				1.40	1.35	0.98	
1075	Middelaar-Witteweg			-0.84	-1.28	-0.23	-1.09	-0.93
1076	Plasmolen-Kloosterberg					-0.02		
1104	Millingen-Eversberg				-1.32	-1.26		
1123	Ingen-De Poel	-0.03	1.84	1.83	-0.55	-0.32	1.94	0.91
1124	Wijchen-Tienakker		0.58	0.85	-0.75	-0.80	-0.16	-1.25
3092	Poeldijk-Wateringseweg					0.27		
3099	Rijswijk-De Bult			0.28	-0.51	0.73		
4083	Naaldwijk-Middelbroekweg		-0.88	1.00	5.17	0.28	0.88	-0.48
4092	Naaldwijk-Hoogwerf	-0.60	-0.57	-1.08	-0.89	-0.67	-0.66	-0.80

n	18*	20*	22*	28	33	23	23
n with $C_B \geq \overline{C_{B\,10\,nn}} + \sigma_{10\,nn}$	6	5	6	7	7	3	4
n with $C_B \geq \overline{C_{B\,10\,nn}} + \sigma_{10\,nn}$ (%)	33.3	25	27.3	25	21.2	13.0	17.4

*Table 6.15. Deviation of the C_B of stone-built rural settlements in the OC-network from the average for the ten nearest settlements ($C_{B\,10\,nn}$), expressed in terms of the standard deviation of that set ($\sigma_{10\,nn}$). Highlighted values are those who deviate by a value larger than 1 σ (dark green = +2 σ; light green = +1 σ; yellow = -1 σ). *Stone-built rural settlements were regular post-built rural settlements at least during the LIA-ERP B interval, and only became stone-built afterwards.*

6.4.4.3 Discussion

The results presented above give rise to some interesting observations about the role of stone-built rural settlements in transport networks. In terms of C_B, the first conclusion is that they do not particularly stand out when considering the entire network across the Rhine-Meuse delta. This stands in opposition to the conclusion that was drawn in our previous case study of the Kromme Rijn region, where stone-built settlements were consistently among the top 20% of settlements in terms of C_B. The explanation for this is that site density in the Kromme Rijn region is relatively homogeneous, whereas site density over the entire Rhine-Meuse delta is quite heterogeneous. The latter situation leads to settlements in less densely inhabited areas that function as bridges primarily between the eastern and western parts of the study area to have a high C_B, even though the actual number of transport movements that go through that site is probably low precisely because there are few settlements in that area.

In order to study the role of stone-built rural settlements in networks of local transport it is therefore more relevant to compare them on a local scale instead of the regional scale, with settlements in their direct vicinity. Table 6.14 shows that for each period in the W20-network on average a third of the stone-built rural settlements exceed the average C_B of the ten nearest settlements by more than one standard deviation. This is more than what would be expected since at all times only 5-7% of all settlements are (or would later become) stone-built. In contrast, occurrences where a stone-built rural settlement is more than one standard deviation below that average are a lot less frequent. This indicates that although not every stone-built rural settlement is always an important site in terms of C_B, they are at least more likely than the average rural settlement in their vicinity to be important in the form of having control over transport movements over the network.

In the W20-network, a total of 17 out of the 33 stone-built settlements that are present in any time period have at one point in time a C_B that exceeds the average C_B of the ten nearest settlements by more than one standard deviation. In 14 instances this happens already within the LIA-ERP B time interval, when the sites in question were very likely still regular post-built rural settlements and not stone-built rural settlements. It can thus be stated that one of the reasons why these particular sites became stone-built in the MRP is the potential that these sites had to control movement over the network in their pre-stone-built phase. This cannot be the only reason however, since there are also 16 stone-built rural settlements that do not particularly stand out within their own environment, and likewise there are other settlements that do stand out in comparison to their neighbours but that as far as we know have not become stone-built.

There is not much difference between the modelled modes of transportation. The W20- and OC-network, and by extension the other walking and animal-drawn cart networks, have largely similar results in terms of the settlements that become important and those that do not, which can be indicative of these settlements having a naturally 'good' position to acquire a high C_B. These settlements tend to be located on bottleneck locations in the landscape and the network, where they are among a limited number of settlements or are even the only settlement that connect two other areas with a larger number of settlements. The landscape, and particularly the way the landscape inhibits or funnels movement, is thus important in defining which settlements become important in local transport networks, but not to the extent that it makes a large difference for different modes of transportation.

In section 6.4.3 stone-built rural settlements were analysed as possible intermediary sites in a hierarchic system of distribution to describe the flow of goods from the rural to the military population. Comparing those results with the ones found here, it is interesting to note that a number of stone-built settlements that do not stand out here in terms of C_B, were able to potentially fulfil the role as intermediary site. This shows that a settlement may have become stone-built for different reasons related to centrality in local transport networks: because they can be reached easily by other settlements, or because they need to be traversed to reach other settlements.

6.4.4.4 Conclusion

The central question asked in this section 6.4.4 is if stone-built rural settlements had a special role in local transport networks that may have lead them to grow in importance, measured in terms of a difference in C_B for the stone-built rural settlements compared to other settlements. By comparing the stone-built settlements against the ten nearest settlements, it was found that roughly one third of them at any time have a C_B that is more than one standard deviation above the average, which is more than what would be expected based on the limited amount of stone-built settlements in the dataset. The majority of these also already have such a high C_B in the LIA-ERP B interval, suggesting that these rural settlements could have become stone-built because they hold such a position where they can potentially control local transport movements. Comparing these results to those found in the previous section 6.4.3 where stone-built rural settlements were tested as potential intermediary sites, it is found that some sites that do not have a high C_B can be good intermediary sites and vice versa, indicating that settlements of this type could have played varying roles in local transport networks and thus also could have grown in importance and become stone-built for varying reasons related to centrality in local transport.

6.5 Continuity and change in transport networks

6.5.1 Introduction

Networks in archaeology are often viewed as snapshots of a certain time period, foregoing the fact that the relations that are studied are continuously changing. This is also the case for transport networks: settlements appear and disappear and sites grow and fall in importance. The archaeological site dataset in combination with the reinterpreted chronological information according to the methodology of Verhagen *et al.* (2016b; see also section 3.4.2) allows for the study of transport networks through time, albeit still limited to the time intervals that are defined in the ARCHIS database. The goal of this section is to study continuity and discontinuity in local transport networks of the Rhine-Meuse delta over the Roman Period.

6.5.2 Data

Similar to the research presented in the previous section (6.4), this study mainly uses the site dataset filtered to only include sites interpreted as settlements that have a 50% or greater probability of being present during a certain time period, following the procedures discussed in section 3.4.2 and Verhagen *et al.* (2016b). This results in a dataset varying in size from 284 for the Late Iron Age (although this is likely inaccurate since the original dataset mostly includes Late Iron Age sites only when they are thought to be continuous into the Roman Period) to 587 for the Middle Roman Period B. The dataset of modelled transport connections is filtered to only include those that are part of the Gabriel graph, constructed using travel time for the separation between places (see sections 6.2.3.4 and 6.2.3.5) (Fig. 6.40). The network that will be analysed here is for walking while carrying a load of 20 kg, although in principle the methodology can be reapplied on other networks as well.

Since part of this study was originally designed as a case study for the application of a reinterpretation of the chronological data (as presented in section 3.4.2), this section will also include a comparison between the modelled networks resulting from the original (expert judgement-based) chronology and networks from a reinterpreted chronology with varying thresholds of probability.

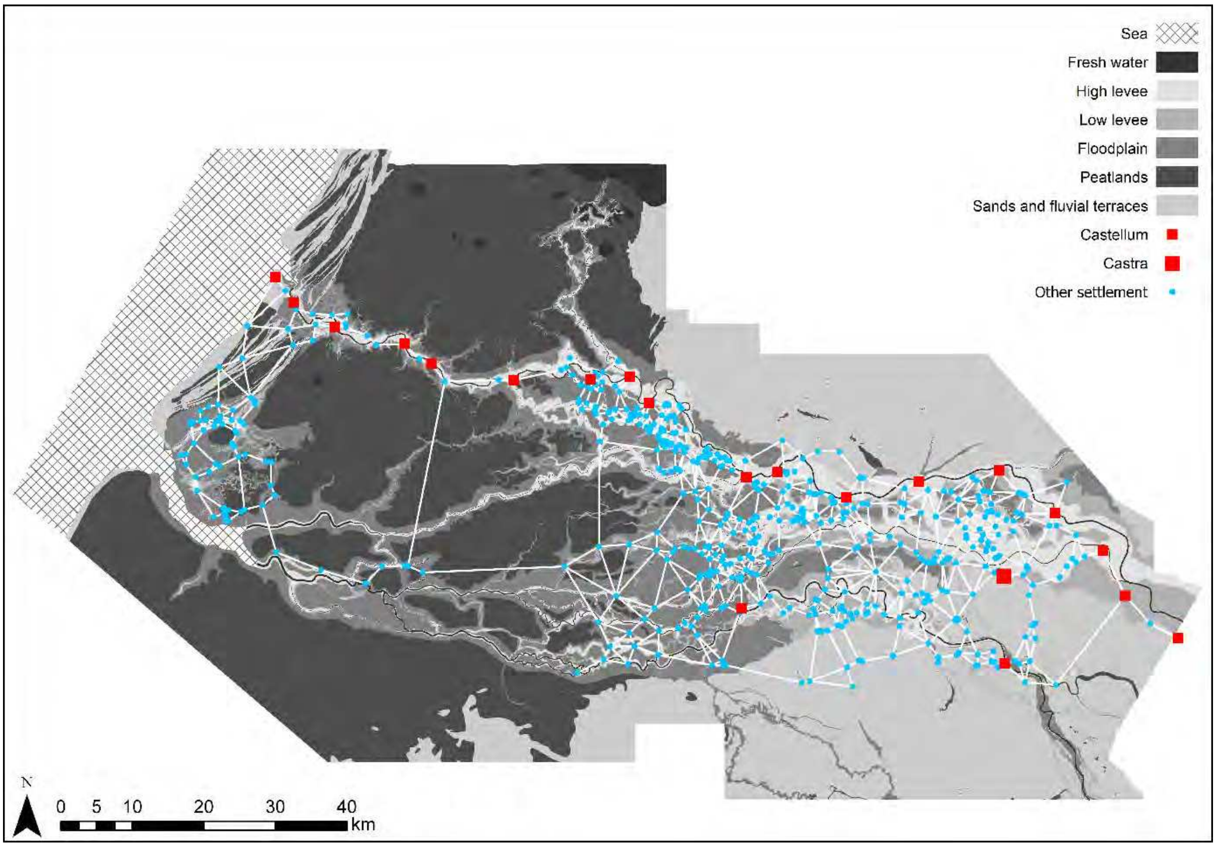


Figure 6.40. The Gabriel graph W20-network of the MRP A. The straight lines in this network are a simplified representation of the transport connections modelled through least-cost paths.

6.5.3 Methodology

It is not easy to establish continuity or discontinuity in potential transport networks modelled on the basis of least-cost paths. Foremost, when is a path continuous over a time interval? Is it necessary for a path to follow the exact route of a predecessor (in the case of least-cost paths almost always necessitating that both the source and destination of the path are continuous over that time interval) or is it enough when paths are within certain bounds in relation to any preceding paths (e.g. analogue to "route persistence" of van Lanen *et al.* 2016). Part of this study is to look at different ways to measure continuity and discontinuity, which will be outlined below. Universal to all methods is that they are measured over the time intervals between the archaeological periods as specified in the ARCHIS database (Table 6.16), as that is also the most detailed chronological information that is available to sites. For example, a part of the network that is present in both the LIA and the ERP A is thus considered continuous over that time interval.

The results start with a comparison of the networks resulting from the reinterpreted chronological information with the one from the original chronological data. In order to focus on that objective, for this part of the study only the MRP A network will be compared. The networks constructed from the reinterpreted chronology will be made using thresholds of 50, 80 and 95% probability of a settlement being present during a time period. Comparisons will be made using some general network measures (see also sections 1.4.6.5-1.4.6.6) to see how much different the networks are from each other.

Iron Age (IA)	Roman Period (RP)						Medieval Period
800 – 12 BC	12 BC – AD 450						AD 450 – 1500
Late Iron Age (LIA)	Early Roman Period (ERP)		Middle Roman Period (MRP)		Late Roman Period (LRP)		Early Medieval Period
	12 BC – AD 70		AD 70 – 270		AD 270 – 450		AD 450 – 1050
	Early Roman Period A	Early Roman Period B	Middle Roman Period A	Middle Roman Period B	Late Roman Period A	Late Roman Period B	Early Medieval Period A
250 – 12 BC	12 BC – AD 25	AD 25 – 70	AD 70 – 150	AD 150 – 270	AD 270 – 350	AD 350 – 450	AD 450 – 525

Table 6.16. Time periods as specified in ABR and ARCHIS, the Dutch national archaeological database. The Roman Period is subdivided between an Early, Middle and Late Period, which in turn are separated into two phases each. In contrast, the Iron Age is not distinguished on three levels.

This methodology assumes that a part of the network is continuous over a time interval when it is within a certain bound of the network of the preceding period. Van Lanen *et al.* (2016) use a 500 m zone to study spatial correlation of routes, partly based on it being the maximum accuracy that can be achieved in their grid resolution. However, part of the reason is also that it cannot be expected that routes have persistently maintained their exact geographic location, since in the Roman Period (as well as the subsequent Medieval Period) routes are almost never fixed through the presence of physical infrastructure. They are not fixed in space and time and can shift over some distance, which is why Willems (1986, 63–64) speaks of routes rather than roads for such connections outside the Roman military roads.

This study employs a similar approach, by calculating the continuity of the modelled transport connections based on their proximity to the younger network with thresholds of 250, 500 and 1000 m. The methodology thus requires the construction of spatial buffers around the least-cost paths that make up the transport network of a certain time period (Fig. 6.41). For the preceding period it is then calculated which sections of the least-cost path network intersect with those buffers, in order to find out what portion of the network is preserved/continued (Fig. 6.42).

As a contrast, an analogue calculation can be made for settlements, especially the ones that newly appear in the younger period. However, this is done the other way around: rather than seeing if the older is within the buffer of the younger (as is done for the routes), this evaluates if the younger are within the buffer of the older. For all settlements that are absent in the older period and present in the younger period, it is therefore calculated if they are within or outside the 250, 500 and 1000 m buffers of the older period (Fig. 6.43).

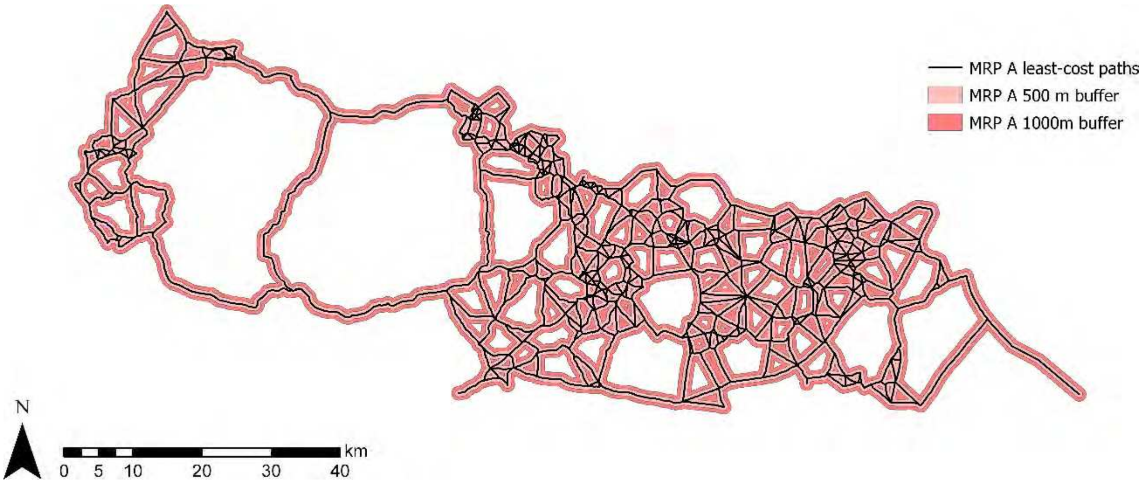


Figure 6.41. 500 and 1000 m buffers around the Gabriel graph network of least-cost paths of the MRP A. The 250 m buffer is not shown due to being nearly indistinguishable from the least-cost path on this scale.

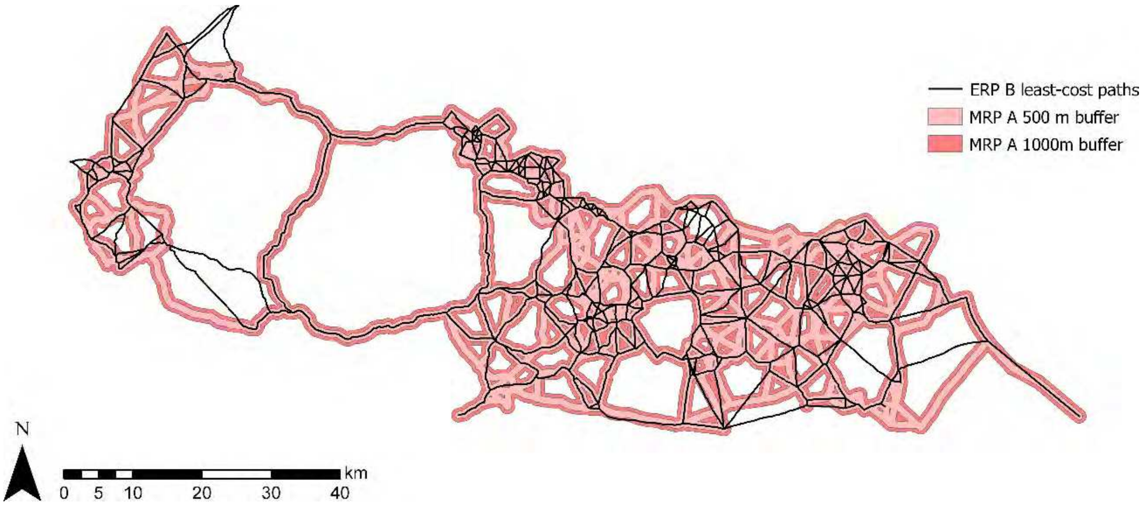


Figure 6.42. Gabriel graph network of least-cost paths of the ERP B, imposed on the 500 and 1000 m buffers around the network of the following MRP A. The 250 m buffer is not shown due to being nearly indistinguishable from the least-cost path on this scale.

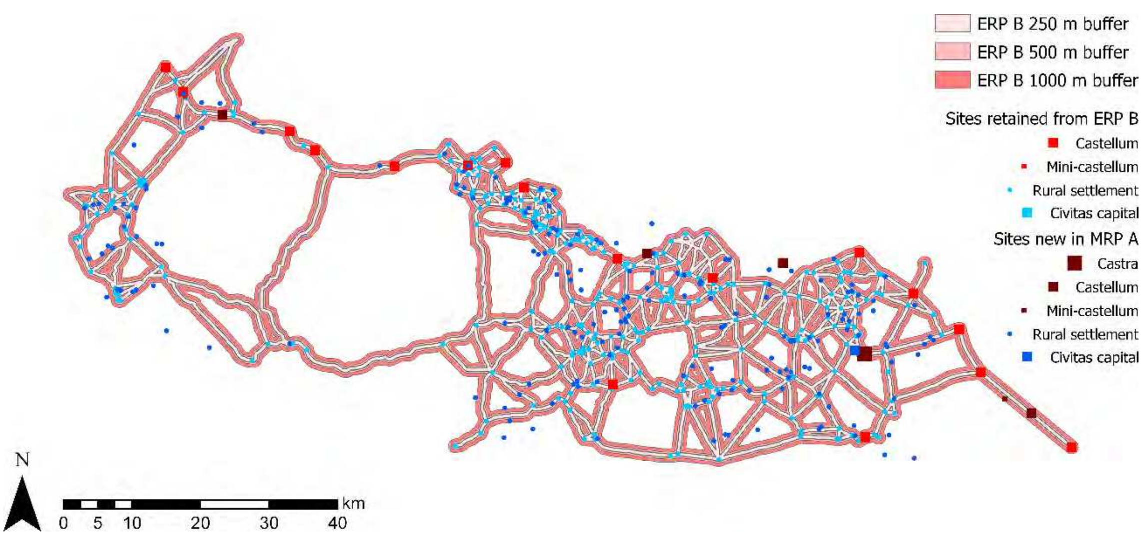


Figure 6.43. Sites of the MRP A, split between those that newly appear and those that are retained from the previous period (ERP B), imposed on the 250, 500 and 1000 m buffers around the network of the ERP B.

6.5.4 Results

6.5.4.1 Evaluation of the chronological reinterpretation

The major direct difference resulting from the application of the reinterpreted chronological information is the decline in number of sites because many sites cannot be dated to a certain time period reliably enough. This can potentially affect the network structure, and for this reason the results of the reinterpreted chronological information for varying probability thresholds are compared against the result of the original chronology. They are shown for the Middle Roman Period A in Table 6.17.

	MRP A (expert judgement)	MRP A ($P_{10finds}$ > 0.5)	MRP A ($P_{10finds}$ > 0.8)	MRP A ($P_{10finds}$ > 0.95)
Number of nodes	1090	525	480	448
Number of links	1903	909	834	774
Average weighted path length	817.185	804.755	805.950	815.931
Average degree	3.492	3.463	3.475	3.455
Network heterogeneity	0.290	0.333	0.338	0.327
Average clustering coefficient	0.200	0.217	0.213	0.207

Table 6.17. Comparison of general network measures of networks modelled with the original chronology and with the reinterpreted chronology with varying probability thresholds for sites being present or absent.

As was already known from the original study (Verhagen *et al.* 2016b), the number of sites drops dramatically at the lowest threshold of 50% probability, going from 1090 to 525 sites in the Middle Roman Period A. Increasing the threshold to 80% or even 95% only decreases the number of sites further to 480 and 448 respectively. This is of course also noticeable in the number of links that make up the network between those sites, which decreases from 1903 to 909 and ultimately 774. However, because of the relatively rigid structure of the Gabriel graph, which automatically fills up holes when sites disappear by linking up sites that are more distant, the general network shape does not change significantly. The average path length (in minutes) stays roughly the same, indicating that travel time over the network does not change much depending on how many sites are present. Similarly, the average degree (the average number of neighbours) and the average clustering coefficient (the extent to which a site's neighbours are also neighbouring each other) show very little change. The largest change is noticed in network heterogeneity between the original and the reinterpreted chronology, but it then changes very little with increasing thresholds. This indicates that networks based on the reinterpreted chronology have a higher tendency to contain hub nodes, or sites that have a large number of neighbours compared to the average site, which seems to be a random variation since the average degree is by nature quite limited in the Gabriel graph.

Concluding from the above, it can be stated that although the number of sites changes drastically between the original chronology and the reinterpreted chronology, the general shape and behaviour of the modelled local transport network does not really change. Knowing this allows for a more reliable application of the reinterpreted chronology to study chronological changes in the network.

6.5.4.2 *Continuity on the basis of proximity to succeeding network*

Table 6.18 presents continuity values of a network, based on the premise that a part of the network is continuous when it is within a certain range of the network of the succeeding time period, and is discontinuous when it is outside that range. To get a better appreciation of how continuity and discontinuity varies through time, the same values are plotted in a graph in Figure 6.44.

		<250 m	250-500 m	500-1000 m	>1000 m
LIA - ERP A	Separate	51.5%	13.9%	16.0%	18.6%
	Cumulative	51.5%	65.4%	81.4%	100%
ERP A - ERP B	Separate	87.4%	3.8%	4.6%	4.2%
	Cumulative	87.4%	91.2%	95.8%	100%
ERP B - MRP A	Separate	74.9%	8.3%	7.2%	9.6%
	Cumulative	74.9%	83.2%	90.4%	100%
MRP A - MRP B	Separate	88.5%	4.7%	3.9%	2.9%
	Cumulative	88.5%	93.2%	97.1%	100%
MRP B - LRP A	Separate	57.3%	11.7%	13.3%	17.7%
	Cumulative	57.3%	69.0%	82.3%	100%
LRP A - LRP B	Separate	93.3%	2.9%	2.1%	1.7%
	Cumulative	93.3%	96.2%	98.3%	100%

Table 6.18. Percentage of path length of the preceding period within a certain range of the network of the subsequent period, expressed as separate (per range) and cumulative (this range and all smaller ranges) values.

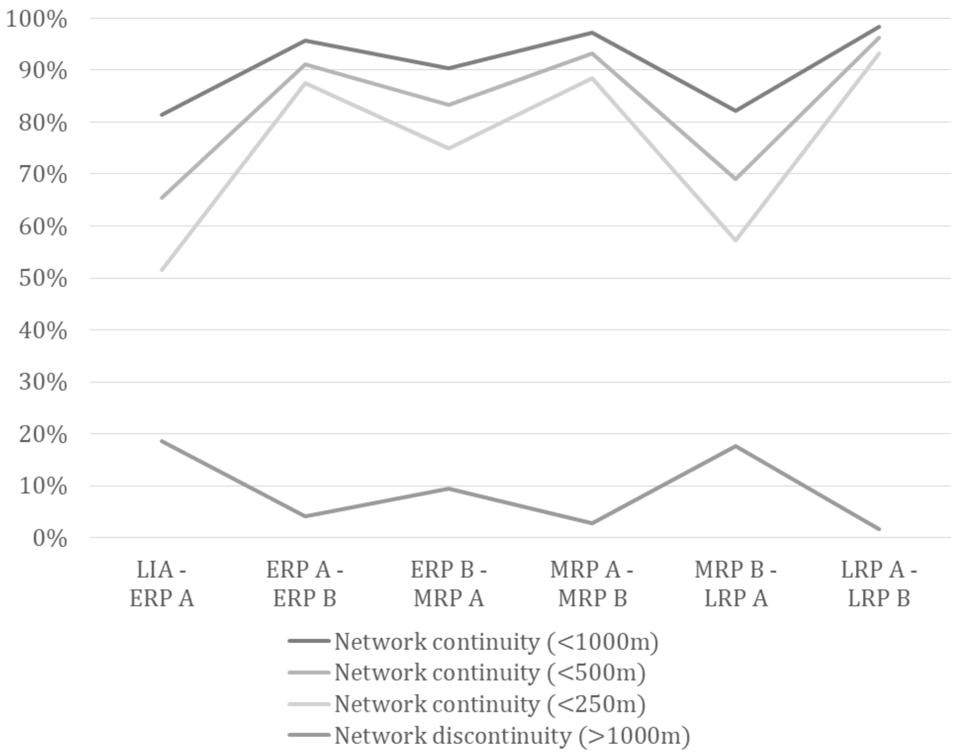


Figure 6.44. Network continuity expressed as percentage of path length of the preceding period within a range of 250, 500 and 1000 m of the network of the subsequent period, and network discontinuity expressed as percentage of path length of the preceding period outside 1000 m range of the network of the subsequent period.

As a comparison, Table 6.19 shows how many of the settlements that newly appear in a period are within range of the network of the preceding period. This can give an indication of the extent to which the continuity of the network is dependent on where new settlements appear (i.e. inside or outside the older network). In similar fashion, Table 6.20 shows how many of the settlements that disappear are within (or outside) the range of the succeeding period, which may be an indication to the extent to which the settlements may have disappeared due to discontinuity in the network.

		<250 m	250-500 m	500-1000 m	>1000 m	Sum
LIA - ERP A	**Separate**	25.2%	23.7%	24.4%	26.7%	131
	Cumulative	25.2%	48.9%	73.3%	100%	
ERP A - ERP B	**Separate**	42.0%	18.9%	17.4%	21.7%	69
	Cumulative	42.0%	60.9%	78.3%	100%	
ERP B - MRP A	**Separate**	37.5%	22.0%	18.7%	21.8%	192
	Cumulative	37.5%	59.5%	78.2%	100%	
MRP A - MRP B	**Separate**	44.6%	20.5%	18.0%	16.9%	83
	Cumulative	44.6%	65.1%	83.1%	100%	
MRP B - LRP A	**Separate**	100%	0%	0%	0%	2
	Cumulative	100%	100%	100%	100%	
LRP A - LRP B	**Separate**	47.6%	21.4%	16.7%	14.3%	42
	Cumulative	47.6%	69.0%	85.7%	100%	

Table 6.19. Sum of new settlements appearing in each period, and percentage of new settlements appearing in range of the network of the preceding period, showing separate values per range and cumulative values for that range and all smaller ranges.

		<250 m	250-500 m	500-1000 m	>1000 m	Sum
LIA - ERP A	**Separate**	30.5%	23.4%	22.7%	23.4%	128
	Cumulative	30.5%	53.9%	76.6%	100%	
ERP A - ERP B	**Separate**	100%	0%	0%	0%	4
	Cumulative	100%	100%	100%	100%	
ERP B - MRP A	**Separate**	26.3%	26.3%	5.3%	42.1%	19
	Cumulative	26.3%	52.6%	57.9%	100%	
MRP A - MRP B	**Separate**	90.0%	3.3%	6.7%	0%	30
	Cumulative	90.0%	93.3%	100%	100%	
MRP B - LRP A	**Separate**	36.2%	23.6%	21.7%	18.5%	254
	Cumulative	36.2%	59.8%	81.5%	100%	
LRP A - LRP B	**Separate**	60.0%	0%	30.0%	10.0%	10
	Cumulative	60.0%	60.0%	90.0%	100%	

Table 6.20. Sum of existing settlements disappearing in each period, and percentage of those settlements disappearing in range of the network of the subsequent period, showing separate values per range and cumulative values for that range and all smaller ranges.

6.5.5 Discussion

On average, around 60% of new settlements appear within 500 m of the network of the preceding period, and around 80% appear within 1000 m. This is interesting information for a study on settlement locations, but also relevant as a comparison to how much of the network is continued. Here the contrast is apparent: at times already 90% of the older network is retained within 500 m of the network of the younger period, and this can rise even up to 98% within 1000 m. Only fairly small parts are discontinued. At the same time, some transitions have a comparably lower amount of continuity, such as the transition between ERP and MRP and from MRP to LRP.

When focussing on the settlements that are abandoned, during most transitions the majority of abandoned settlements are within a 1000 m range of the transport network of the succeeding time period. This indicates that the abandonment of these settlements is likely not caused by a shift in networks of transport, as the network continues to exist after the disappearance of the settlements. Along that line of thought, despite the network being modelled using settlement locations as nodes, the resulting network is relatively robust and its exact structure is not necessarily dependent on a few settlements disappearing. A similar conclusion was reached when studying the robustness of network analysis results (section 6.3). The only noticeable exception is the ERP B-MRP A transition, where 42% of abandoned settlements are outside a 1000 m range. The reason that these sites were abandoned may thus be that they were on inefficient parts of the network that were subsequently discontinued.

Looking at these variations in network continuity, plotted also in Figure 6.44, the first point of noticeable discontinuity is the shift from the LIA to the ERP. This may in part be caused by the incompleteness of the site dataset in the Late Iron Age. However, this may also be the result of instability in the region. For the southwestern Netherlands, Van Heeringen (1988) notices a dip in habitation and discontinuity in material culture, and relates this to a possible increased wetness of the landscape and group migrations. Another possibly major factor of instability in the Late Iron Age may be Caesar's campaigns in the region, culminating in the defeat of the tribes of the *Tencteri* and the *Usipetes* near the Late Iron Age confluence of the Meuse and Waal rivers (Roymans 2017).

Other dips in network continuity can be tied to major changes that are known to have happened in the Roman Period. The shift from the ERP to the MRP is marked by the Batavian revolt (AD 69-70; Brunt 1960), a period of major instability in which many of the forts along the Rhine were temporarily abandoned by the Roman military. This may have resulted in an upheaval of the socio-economic structure of the rural hinterland as well. Slightly earlier than the ERP-MRP transition is the arrival of immigrant groups from north of the Rhine that became part of the Cananefatian *civitas* around AD 50, as argued by De Bruin (2017) on the basis of material culture, possibly influencing the dip in continuity that is noticed during the ERP-MRP transition.

Another major shift that may have caused a dip in continuity of transport networks is the 3rd century border collapse, marking the MRP to LRP transition. Similar patterns are seen in the settlement dataset, indicating that the more significant changes in the settlement pattern over these transitions also result in more significant changes in local transport networks. However, larger parts of the network are retained than would perhaps be expected based on the levels of discontinuity in the settlement dataset, showing again that the general structure of this network of transport is relatively robust and not entirely dependent on the exact configuration of settlements on which it was modelled.

6.5.6 Conclusion

This study presented in this section aimed to study continuity and change in local transport networks using an archaeological site dataset with a reinterpreted chronology. It was shown that there was little structural and functional difference between the networks generated from the original chronology and those from the reinterpreted chronology with varying thresholds. Based on the more reliable information from the reinterpreted chronological dataset, it could be shown that large parts of the network are retained within a certain range of the subsequent network. The network structure is also not dependent on the abandonment of a few settlements, as the majority of those abandoned settlements are still within range of the network of the succeeding period. For some transitions between the archaeological time periods the continuity was higher than 90% within a 500 m range. However, there are noticeable dips in continuity, that seem to coincide with transitions that we know from archaeology to be more unstable time periods, such as the Batavian revolt between the ERP and MRP, and the 3rd century border collapse between the MRP and the LRP.

6.6 Conclusion

The goal of this chapter was to study local transport networks of the Dutch part of the Roman *limes* with concepts of network science. In each section one or more problems were identified, which included both methodological and archaeological questions, and an approach was sought to address these problems.

In section 6.2 a comparison was made between various network construction techniques, to find the network structure that is closest to the archaeological reality it aims to represent. This was a necessary step that had to be undertaken in order to move from the dataset of potential transport connections modelled through a least-cost path approach (see Chapter 5) to a network that can be analysed with concepts from network science. By setting some evaluation criteria that are archaeologically relevant, such as how easy it is to move goods from rural settlements to the *castella*, measurable through the average path length, a quantitative evaluation could be made of various network construction techniques. In this case the Gabriel graph was found to be the best network structure representation of a local transport network for the distribution of goods from the local to the military population, but similarly important, this section has demonstrated an approach in which such a methodological problem can be suitably addressed with the archaeological reality in mind.

The application of network analysis techniques on archaeological networks also give rise to questions of uncertainty: how dependent are the results for instance on the completeness of the dataset? Section 6.3 aimed to study the effects of uncertainty on network analysis results, by constructing a model that iteratively builds networks from the existing datasets so that the dependency of network measures on the completeness of the network structure could be evaluated. It was found that 64% of the sites had a robust measurement, meaning that the results are not dependent on that specific network structure but would remain the same when for instance sites are missing from or are falsely present in the dataset. On the other hand, 36% is thus not that reliable, and this must be kept in mind when applying network analysis on archaeological datasets. An important aspect of this study is that it presented a methodology through which such a question of uncertainty with the archaeological datasets in mind can be addressed.

Section 6.4 focussed on the application of network analysis on the modelled transport networks. The first case study tested an archaeological hypothesis of Vos (2009) and Willems (1986), who posited that the (re)distribution of goods in the Dutch part of the Roman *limes* was achieved through a hierarchic dendritic system, where intermediary sites functioned in between the military population in the *castella* and the local population in the rural settlements. This hypothesis was tested by contrasting two hypotheses: a null hypothesis in which all surplus produced goods flow directly to the *castella*, and the alternative hypothesis in which goods were gathered first at predetermined intermediary sites before moving to the *castella* in bulk. The network measure of path length (which equates travel time in our study) was used to evaluate these hypotheses, and it was found that in most cases distribution through the intermediary site was more efficient than a direct distribution, making the alternative hypothesis that was posited by previous archaeological studies more likely than our null hypothesis, although there is also room for a dual system in which both methods of distribution of goods co-existed. This study is a good showcase of how an archaeological idea can be tested and thus given more weight by expressing the problem in more explicit hypotheses that can be evaluated using concepts of network science.

The second case study in section 6.4 studied the role of stone-built rural settlements in a bit more depth. More particularly, the question was asked if these stone-built rural settlements had a potential control over transport movements in the network that may have led them to becoming more important over time, a property that can be evaluated using the network measure of betweenness centrality. It was found that a number of stone-built rural settlements had a higher betweenness centrality than the average settlement in their neighbourhood, and this number was greater than would be expected on the basis of the ratio of rural settlements that are stone-built. Interestingly, in most instances this was already the case in the Late Iron Age or Early Roman Period, i.e. the pre-stone-built phase of these settlements. This could thus indicate that part of the reason that these sites have become important and ultimately have become stone-built is that they have a potential to control transport movements over the network. This study is a good showcase of how network measures can be used to study the role that individual settlements have played in transport networks.

In section 6.7 the reinterpreted chronological information following the methodology of Verhagen *et al.* (2016b; see also section 3.4.2) was used explicitly to test continuity and change in transport networks through time. It was found that the application of this new chronological information did not significantly change the resulting network structures compared to the original chronology, which is an important conclusion because otherwise the results of any analyses would only be dependent on the chronological methodology applied. Instead, the reinterpreted chronology could be used to study changes with more chronological reliability. This study revealed that there is a high degree of continuity in local transport networks, and this continuity is higher than would maybe be expected on the basis of continuity in the settlement dataset, indicating that local transport networks are more persistent than the settlement pattern itself. Some variations were also noticeable in the level of continuity, which could be related to known periods of instability such as the Batavian revolt and the 3rd century border collapse.

7 Site location analysis

7.1 Introduction

The location of settlements in the natural landscape has long been of interest to archaeologists, and in the Netherlands research on this topic has had a traditional following in processual archaeology and later in the rise of predictive modelling (e.g. Brandt *et al.* 1992; Verhagen 2007). Relatively recently, a qualitative analysis of the location of Roman *castella* in the western Netherlands challenged the traditional assumption that these *castella* were located on higher points in the landscape, showing that the majority are actually located on low and wet (yet strategic) locations along the river Rhine (Van Dinter 2013). Vossen (2007) also noted that some well-researched rural sites were located on the flanks of channel belts instead of the highest ground (see also Groot *et al.* 2009). Yet, a quantitative analysis of settlement location preferences in the area has not been performed up to now.

In this research we are interested in site location for several reasons: to determine the (natural, cultural/social or historical) governing factors of settlement location choices, to investigate settlement pattern development through time, and to serve as input data for models of agricultural production. A preliminary study to analyse settlement location in the natural landscape has already been performed to some extent (Verhagen *et al.* 2016b, 314–16), and the results will be elaborated and expanded upon in sections 7.3.1.1 and 7.4.1.1.

Besides site location related to palaeogeography, the subject of the preliminary study, other aspects may also have played a role in site location. For this reason a number of other factors will be analysed, namely (distance to) rivers and streams, forts, transport networks, potential intermediary sites in transport networks, and the influence of the historical landscape (previously existing settlements).

The analyses carried out as part of this study will be done in two parts. Firstly, the individual factors will be elaborated and analysed. Secondly, in order to study the relative importance of factors and how that possibly changes through time, a multivariate approach is applied.

7.2 Data

This section serves as the introduction to the datasets that are used in this study. They consist of the palaeogeographic reconstruction (introduced in Chapter 2), the archaeological site dataset (Chapter 3) and the modelled transport networks (Chapters 4, 5 and 6).

7.2.1 Natural palaeogeography

The reconstructed palaeogeographic map was presented in Chapter 2 and will be used in this analysis. The preliminary study showed that for a site location analysis the palaeogeographic units can best be simplified into seven categories, representing a certain land use potential rather than the original geomorphology (Verhagen *et al.* 2016b, 315). The applied transformation is shown in Table 7.1.

Palaeogeographic unit	Simplified palaeogeographic category
High natural levees	High natural levees
Moderately high natural levees	
Low natural levees	Low natural levees
Residual gullies	
High floodplains	Floodplains
Low floodplains	
Eutrophic peatlands	Peatlands
Mesotrophic peatlands	
Oligotrophic peatlands	
Dunes and beach ridges	Sands and fluvial terraces
Coversands	
River dunes	
High Pleistocene sands	
Fluvial terraces	
Rivers and streams	Fresh water
Lakes	
Tidal flats	Sea and tidal flats
Sea	

Table 7.1. Transformation of palaeogeographic units into simplified palaeogeographic categories.

7.2.2 Site dataset

This study will apply an analysis of site location specifically on archaeological sites that have been interpreted as rural settlements. Other sites, including *castella*, *castra* and potential intermediary sites such as *vici* play a role as a potential influencing factor in this analysis. The rural settlements include both stone-built and post-built variants. In order to avoid uncertainty in the site dataset playing a role in the site location analysis, the settlement dataset must be filtered for reliability. Similarly to the studies presented in previous chapters, this study therefore only includes sites that have a probability of 50% or greater of having 10 or more finds dating in a specific period (section 3.4.2; Verhagen *et al.* 2016b). Out of the original 1081 rural settlements, this leaves 607 settlements that surpass this threshold during any time period of the Late Iron Age and Roman Period.

By including a probability threshold for a site being present during a certain time period, the chronological uncertainty in the site dataset is reduced. However, considering that the palaeogeography is an important aspect of the site location analysis, spatial uncertainty in the site dataset is another relevant factor to take into account. It is important to realise that the recovery rate of archaeological sites is probably not homogeneous across the research area. For instance, sites may have disappeared through fluvial erosion. A good example is the lower reach of the Meuse, where the low site density can more likely be explained by fluvial erosion (including the St. Elizabeth flood of 1421) rather than an actual low population density in the Roman period. Because the number of sites that have not been recovered is unknown and can at best be only estimated, it may be more practical to filter the site dataset to only include sites that are in (palaeogeographic) areas that have a high certainty. This can be done using the known sources of uncertainty in the palaeogeographic map, presented in section 2.5. The sources of uncertainty that were mapped there are post-Roman fluvial erosion (based on Cohen *et al.* 2012), post-Roman coastal erosion (based on 19th century and modern topographic maps), post-Roman drift sand deposits (based on an overlay of the soil map and geomorphological map; Alterra 2006; 2008), peat reclamation and exploitation (based on 19th century maps and peat mapping studies; Stouthamer *et al.* 2008; Bekius and Kooiman 2016), plaggen soil coverage (based on the soil map) urban development (based on the soil map, geomorphological map and LIDAR data), other anthropogenic elements such as dikes, embankments, dwelling mounds, quarries, excavated areas and levelled areas (based on the soil map and geomorphological map) and modern surface water (based on the geomorphological map).

By assigning each of the sources of uncertainty a value of 1, and then summing these uncertainty values, an uncertainty map can be created for the palaeogeographic reconstruction. This results in a map with uncertainty sums ranging between 0 (certain) and 5 (uncertain). An uncertainty sum of 5 only occurs when post-Roman fluvial erosion, peat reclamation and excavation, urban development, other anthropogenic elements and surface water overlap, which is only found as a results of inaccurate mapping. Normally surface water does not overlap with urban development or other anthropogenic elements, and thus the more commonly found maximum uncertainty sum is 4.

The uncertainty sums can be extracted to the point data of the 607 sites that are present at this point in the analysis (Fig. 7.1). The results are shown in Table 7.2. It can be seen that almost half of the sites are located in areas where there is no uncertainty, and nearly 40% in areas with an uncertainty sum of 1. In comparison, the total land area covered by uncertainty sums of 0 and 1 is almost equal for both values at 41%. For an uncertainty sum of 2, the total land area covered is 17%, whereas the percentage of settlements in that area is only 12%. This suggests that sites are more likely to appear in areas with an uncertainty sum of 0, and less likely in areas with an uncertainty sum of 2. However, this difference in site recovery rate cannot simply be attributed to the difference in uncertainty; some areas with high uncertainty sums may have been less attractive for habitation in the first place, such as peatlands. On the other hand, this is also the case for some areas with uncertainty sums of 0 (e.g. the high Pleistocene sands north of the Rhine).

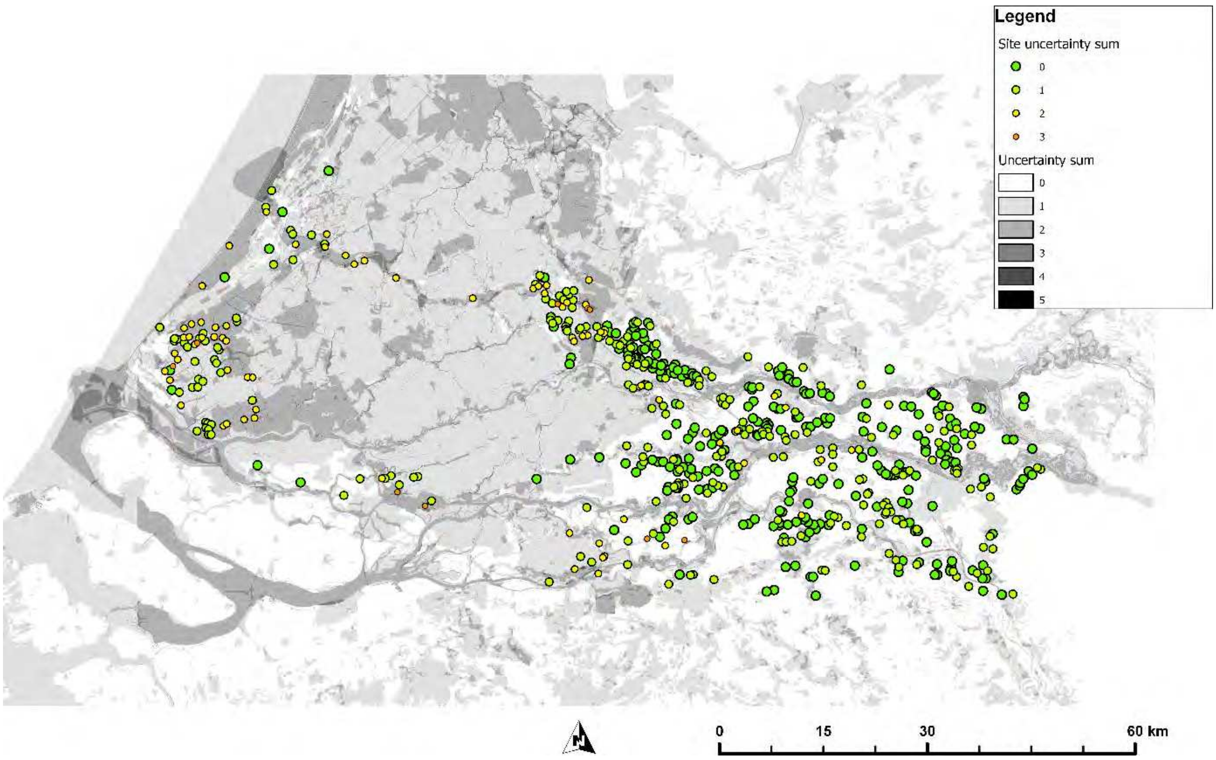


Figure 7.1. Distribution of uncertainty sums per site over the map of uncertainty sums.

Uncertainty sum	Number of settlements	Percentage of settlements	Land area (km^2)	Percentage of total land area
0	287	47.28	4154.7	40.99
1	240	39.54	4151.7	40.96
2	71	11.70	1688.1	16.65
3	9	1.48	139.3	1.37
4	0	0	2.9	0.03
5	0	0	0.01	0.00
Total	607	100	10136.7	100

Table 7.2. Number and percentage of rural settlements that fall within a certain uncertainty sum value, compared against the (percentage of) total land area that is covered by that uncertainty sum value.

However, the uncertainty sum at the exact point location assigned to the rural settlement is not the best way to filter the dataset for spatial certainty. Firstly, the coordinates assigned to the settlement may not be accurate. Secondly, for the site location analysis the environment of the settlement is more interesting than just the palaeogeographic unit at the point location alone. In order to know the spatial uncertainty of the environment of the site, the uncertainty sum can be calculated for a certain range of each settlement. Any range number would ultimately remain arbitrary, but a preliminary study has shown a value of 500 m to be quite distinctive in terms of palaeogeographic diversity; greater ranges will result in more homogeneity while small ranges will result in many short-distance changes. Furthermore, this will get closer to the maximum spatial uncertainty of the site coordinates (Verhagen *et al.* 2016b, 315), as the range of observations that are grouped into sites during the construction of the site dataset was set at a 250 m radius (see section 3.2.2) based on a larger perspective on Roman settlement territories also outside the Dutch river area (Nuninger *et al.* 2016, 5, with sources). A 500 m radius was thus modelled for each site, and for each one of those buffers the average uncertainty sum was calculated. The results are shown in Table 7.3. Alternatively, the mode of the uncertainty sums could have been used instead of the average, which in this study would have given a similar output.

Average uncertainty sum	Number of settlements	Cumulative number of settlements
0-0.1	139	139
0.1-0.2	53	192
0.2-0.3	41	233
0.3-0.4	39	272
0.4-0.5	29	301
0.5-0.6	23	324
0.6-0.7	34	358
0.7-0.8	19	377
0.8-0.9	30	407
0.9-1.0	43	450
1.0-1.1	26	476
1.1-1.2	18	494
1.2-1.3	14	508

Average uncertainty sum	Number of settlements	Cumulative number of settlements
1.3-1.4	16	524
1.4-1.5	10	534
1.5-1.6	12	546
1.6-1.7	14	560
1.7-1.8	8	568
1.8-1.9	5	573
1.9-2.0	12	585
2.0-2.1	10	595
2.1-2.2	1	596
2.2-2.3	5	601
2.3-2.4	4	605
2.4-2.5	2	607

Table 7.3. Number of rural settlements within ranges of average uncertainty sums and cumulative number of rural settlements up to and including that average uncertainty sum range.

In Table 7.3 it can be seen that 450 rural settlements, or 74% of the total, have an average uncertainty sum below or equal to 1. Using just the point location the total number of settlements with an uncertainty sum below or equal to 1 was 527, or 87% of the total. Because the average uncertainty sum is an indication of the uncertainty of the palaeogeography of a settlement's environment rather than the point location, for the site location analysis this is a more reliable measure to filter the dataset for spatial certainty. From this point onwards, to reduce spatial uncertainty this study will therefore only include the 450 rural settlements that have an average uncertainty sum of their 500 m buffer that is lower than or equal to 1 (Fig. 7.2). However, it must be kept in mind that this is merely a reduction in spatial uncertainty and not an elimination of that uncertainty, as besides uncertainty due to aspects of erosion (e.g. fluvial) or burial (e.g. through plaggen soils), there are also other factors that may contribute to variation in site recovery rate. One important aspect which is difficult to quantify is research intensity. The area around Nijmegen, and the fluvial levees of the central and eastern Rhine-Meuse delta in general, have been quite intensively studied. In comparison, the western half of the research area has some regions which appear entirely blank but were likely inhabited to some extent as well.

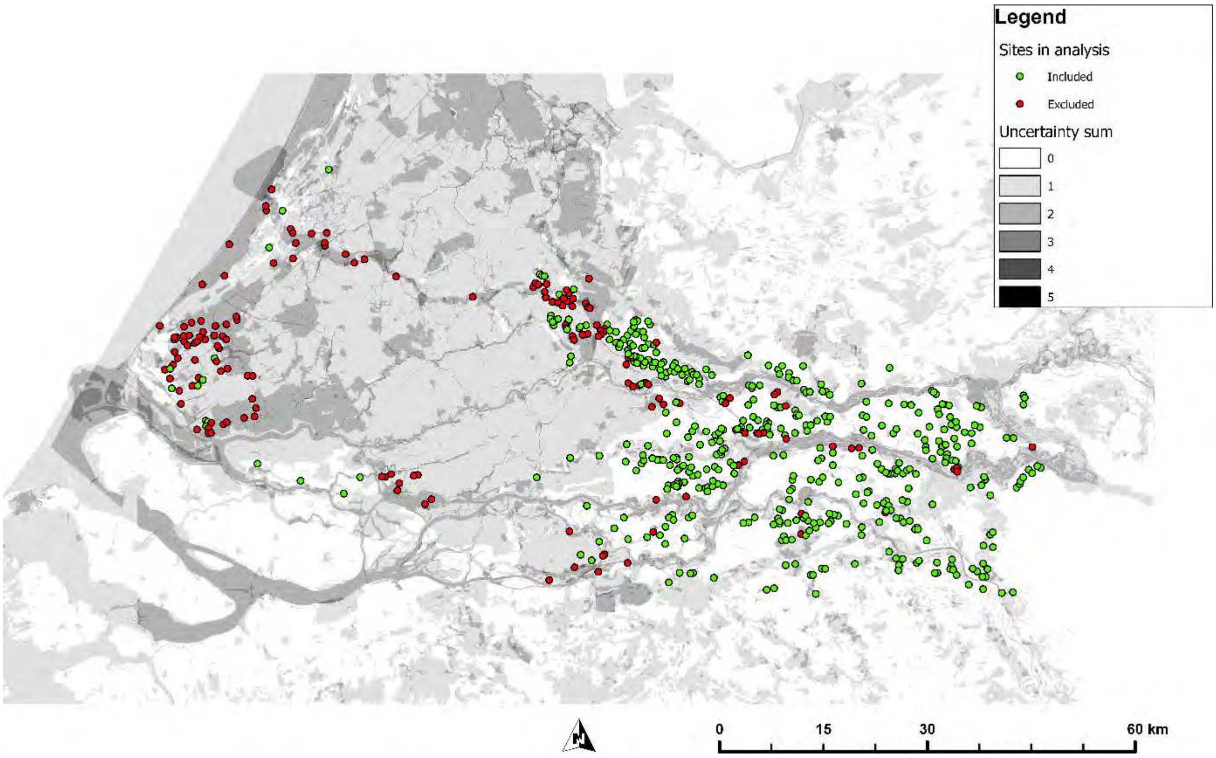


Figure 7.2. Overview of sites included in the analysis on the basis of an average uncertainty sum below or equal to 1, and sites subsequently excluded.

7.2.3 Transport networks

Transport connections and transport networks have been modelled and analysed in Chapters 5 and 6. Multiple network structures have been compared (section 6.2; Groenhuijzen and Verhagen 2017), but they cannot all simply be included in the site location analysis. The comparison has shown that the Gabriel graph is the best representation of a local transport network without great downsides (Groenhuijzen and Verhagen 2017, 250), and therefore this network structure will be implemented in this study (Fig. 7.3). It is important to note that this network is constructed on the basis of a larger site dataset, as presented in section 6.2; it uses all settlements that have a 50% or greater probability of having 10 or more finds in a certain time period and includes rural settlements, *vici* and towns, *castella* and mini-*castella*. The reason for this is that constructing a network for just the 450 rural settlements studied in the site location analysis would leave out many (potentially important) connections.

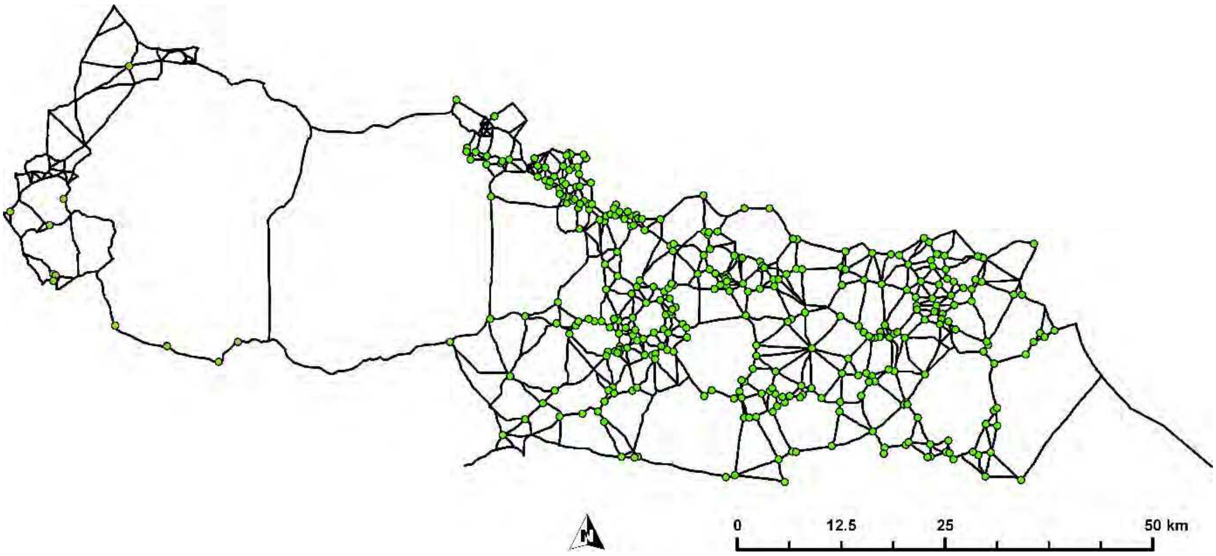


Figure 7.3. Modelled transport network with Gabriel graph structure for the MRP A, with rural settlements of the MRP A that are included in this analysis.

7.3 Methodology

As has been mentioned in the introduction, the site location analysis will be performed in two parts. Firstly, the individual variables will be analysed independently, to get an idea of what the potential influence of this variable is on site location. Secondly, a multivariate analysis will be applied to study the behaviour of the various factors together. Both this section on the applied methodologies and the following section on results are divided along these lines.

7.3.1 Individual variable analysis

The factors that will firstly be studied here independently are the natural palaeogeography, (distance to) rivers and streams, forts, transport networks, potential intermediary sites in transport networks, and the influence of the historical landscape (previously existing settlements).

7.3.1.1 Natural palaeogeography[1]

In this study, the palaeogeographic reconstruction is simplified into seven palaeogeographic categories, as presented in section 7.2.1. Various radii around the settlements are tested (cf.

[1] The content of this section is partly based on p. 314–16 of **Verhagen, P., I. Vossen, M. R. Groenhuijzen, and J. A. Joyce. 2016b. "Now You See Them, Now You Don't: Defining and Using a Flexible Chronology of Sites for Spatial Analysis of Roman Settlement in the Dutch River Area."** ***Journal of Archaeological Science: Reports*** **10: 309–21. doi: 10.1016/j.jasrep.2016.10.006.** Research design by PV, MG and JJ; data provided by PV, IV and MG; chronological reinterpretation by PV; case studies by PV and MG; discussion and conclusion by PV.

Verhagen *et al.* 2013b), with the 500 m and 20 km radius yielding the most illustrative results. The selection of these particular radii can also be justified archaeologically: the 500 m radius shows the core habitation area of a settlement and its immediate surroundings, while the 20 km radius covers the total range of areas that could be exploited by the inhabitants of a settlement within approximately a day's two-way travel.

A hierarchical clustering approach (Anderberg 1973) is used to examine the composition of the dataset and identify a limited number of settlement location typologies to which sites can be assigned. Squared Euclidian distance is used as a distance measure, which emphasises large dissimilarities over small ones in the dataset. Between-groups linkage is chosen as a clustering method, in which the distance between clusters is calculated as the average distance of all points in the clusters. The number of clusters needed for suitable coverage of the dataset was determined through principal component analysis. With the goal of creating an interpretable division of variables onto separate components, the number of components to retain was decided using the criterion of 80% of the total variance accounted for. Using an eigenvalue > 1 criterion (in which only clusters are retained that have a greater variance than the input variables) always results in a division into two components, which, due to the difficulty of meaningful explanation, is disregarded.

In order to validate the consistency of clustering, a silhouette analysis is applied (Rousseeuw 1987). This method measures for each data point how similar it is to its own cluster in relation to other clusters on a scale of -1 to 1, and the average of all data points may be seen as a measure of the quality of clustering.

Using the results of the cluster analysis (and after validation through the silhouette analysis), settlement location strategies may be identified, as well as changes in settlement location preferences through time. The analysis is applied on the 450 settlements selected earlier, a number that differs from the preliminary study (Verhagen *et al.* 2016b, 314–16). Because the focus of that study was on the effects of the chronological reinterpretation, all sites classified as rural settlements were included, regardless of spatial or chronological reliability.

7.3.1.2 Rivers and streams

The analysis of site location in relation to rivers and streams is fairly straightforward. It makes use of the 'rivers and streams' unit of the reconstructed palaeogeography, and the distance to the nearest river or stream is calculated for each of the 450 settlements.

7.3.1.3 Forts

Similar to the analysis of site location in relation to rivers and streams, the analysis of location in relation to *castella* and *castra* is simply performed by calculating the distance of each settlement to the nearest *castella* or *castra* of the preceding period. Especially interesting is to see whether there are changes through time, as the forts as part of the Roman Period cultural landscape have no precedent in the preceding Iron Age. Each time period thus has to be analysed separately, since not all settlements and not all forts are contemporary. An interesting question that can be posed is: do new settlements tend to appear closer or further away to existing *castella* than the already existing settlements?

7.3.1.4 Transport networks

Transport networks are another part of the cultural landscape that are dynamic throughout time. This study uses transport networks modelled following a Gabriel graph structure, as an earlier study has shown this to be the best representative of a transport network in the Dutch part of the Roman *limes* (section 6.2; Groenhuijzen and Verhagen 2017, 250). The networks are modelled using the entire dataset of sites that have a probability of 50% or greater of having at least 10 finds in a certain time period, rather than just the 450 rural settlements used for the location analysis. This is done to ensure that the number of potentially important links missing is as low as possible.

The analysis of site location in respect to transport networks is done per time period by calculating for each site newly appearing in that time period the distance to the network of the preceding time period. This is not unlike to the analysis performed earlier in the context of continuity of transport networks (section 6.5), the only differences being that it is now performed for just 450 rural settlements and that it calculates the exact distance of a settlement to the network rather than a settlements position within buffered zones. In contrast to the analysis of the distance to forts, no comparison can be made with settlements that are continuous of the preceding period. This is the result of the network being constructed on the basis of the site dataset, causing sites that are continuing from a preceding time period to always have a distance of 0 to the network of that period.

7.3.1.5 Intermediary sites in transport networks

In the analysis of transport networks, a number of potential intermediary sites were identified that could have played a role in the flow of goods from the rural to the military population, on the basis of these sites being towns, *vici* (not associated with forts), stone-built, larger than average, or because they contain a *horreum* (section 6.4.3). In the current analysis the question is whether or not these potential intermediary sites have influenced new settlement locations. This will be explored in a similar fashion as for the forts, by calculating the distance of new rural settlements to the potential intermediary sites of the preceding time period.

7.3.1.6 Historical landscape

New settlements do not appear in an empty landscape, and this is incorporated in earlier analyses by looking at forts or transport networks that were existing in the preceding time period. However, the cultural landscape also includes other settlements, and this analysis therefore looks at the influence of previously existing settlements on settlement location. This analysis is performed for the 450 rural settlements included in this study only.

The analysis applied in this study roughly follows a methodology developed in Nuninger *et al.* (2016) and Verhagen *et al.* (2016a). It makes use of the concept of 'memory of landscape' or 'land use heritage'. In this method each location in the landscape is assigned a value that represents the intensity of previous occupation in its surroundings, taking into account both the spatial and temporal distance to previous occupation (Nuninger *et al.* 2016, 3). This value is calculated for each raster cell using a kernel density function, resulting in a 'heritage map'. The Epanechnikov-fuction (Epanechnikov 1969; Silverman 1986, 76) is used as a non-linear distance decay function with a 1000 m radius, as this function was found to be a better estimate of the heritage and the resulting attractiveness of the landscape (Nuninger *et al.* 2016, 5–6). The heritage effect of a settlement is weighted according to the duration of occupation, with the weight decreasing by 0.2 per time period. However, it is difficult to express the duration of occupation in exact number of years, due to the disproportional length of the LIA especially when compared to the later ERP A and ERP B. This would result in a situation where, even with the weight decrease, LIA settlements have a larger potential impact on the MRP habitation pattern than ERP settlements. To circumvent this, each time period is weighted equally. For example, using a standard weight of 100, a settlement occupied in the LIA-ERP A time span will thus have a weight of $100 \times 1 + 100 \times 0.8 = 180$ in the ERP B, a weight of $100 \times 0.8 + 100 \times 0.6 = 140$ in the MRP A, and so on.

Since this study does not include data on habitation prior to the LIA, the heritage values tend to increase over time as more time periods become part of the heritage value calculation. For this reason, the heritage map is normalised by reclassifying the heritage values that are above 0 into quantiles following the same procedure applied by Nuninger *et al.* (2016, 8–9), creating categories of very high (4), high (3), medium (2), low (1), and no (0) heritage. These categories can be used to make comparisons across time periods.

7.3.2 Multivariate analysis

Multivariate analysis has often been used in archaeology in the context of archaeological predictive modelling, to aid in archaeological heritage management as well as to understand the driving factors of settlement patterns (e.g. Kohler and Parker 1986; Woodman and Woodward 2002). This study applies binomial logistic regression to investigate the relationships among and the individual importance of the possible variables for rural settlement location in the Dutch part of the Roman *limes*.

The dependent variable of the regression model is binary: a rural settlement is either present or absent at a specific location. In order to configure the model on site presence as well as site absence, a dataset is needed of non-site locations to include in the model alongside the current data of settlement locations. This dataset is created by randomly distributing 10000 points for each time period, with the condition that none of these points can be within 500 m of the settlement locations of that time period. This was done with the aim to create a stronger contrast between site and non-site locations particularly in the natural palaeogeography, which uses 500 m clusters rather than point data. Alternatively, but not performed in this study, random points could have been placed over site locations as well, to create a comparison between site locations and the average 'background'. Furthermore, in this study the random points were distributed only in those areas for which the palaeogeographic reconstruction has an uncertainty sum equal to or lower than 1 (section 7.2.2), similar to the filter applied on the rural settlement dataset. This was done to prevent areas excluded from the analysis to dominate the areas of site absence and obscure potential zones of site absence within the remaining areas.

The independent variables can be categorical or continuous, and in this case are made up of the natural palaeogeography (500 m clusters), distance to rivers and streams, distance to forts, distance to transport networks, distance to potential intermediary sites, and the historical landscape (Table 7.4). Since many of these rely on elements present in the preceding time period, the LIA uses only the natural palaeogeography and the distance to rivers and streams. In the ERP A all variables are used with the exception of distance to forts (of the preceding time period), since there are no forts in the LIA. The independent variables can be directly extracted to the 450 settlements to be used in the logistic regression, with the exception of the natural palaeogeography, which uses the 500 m clusters that are the result of the individual variable analysis (see section 7.4.1.1 for more detail on the clusters). Similarly, the independent variables are extracted to the non-site locations, with the natural palaeogeography cluster membership based on proximity to the clusters found in the analysis of the settlements. Since the natural palaeogeography cannot be included in the logistic regression as a categorical variable, it is transformed into three binary dummy variables (here called Palaeogeography 2, 3 and 4), using cluster 1 as the reference (e.g. when a site is part of cluster 2, the dummy variable Palaeogeography 2 is set to 1 and all others are set to 0; when a site is part of cluster 1, all dummy variables are set to 0).

<table>
<tr><th>Variable</th><th>Type</th><th>LIA</th><th>ERP A</th><th>ERP B</th><th>MRP A</th><th>MRP B</th><th>LRP A</th><th>LRP B</th></tr>
<tr><td>Natural paleogeography</td><td>Categorical</td><td colspan="7">✓</td></tr>
<tr><td>Distance to rivers and streams</td><td>Continuous</td><td colspan="7">✓</td></tr>
<tr><td>Distance to forts</td><td>Continuous</td><td></td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Distance to transport networks</td><td>Continuous</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Distance to potential intermediary sites</td><td>Continuous</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>Historical landscape (heritage categories)</td><td>Continuous</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
</table>

Table 7.4. Overview of independent variables, with indication of the time periods for which they are available.

This study uses a Monte Carlo method approach to develop a logistic regression model for each time period. The entire process is modelled in R (R Core Team 2013), with the general working of the model shown in a flowchart in Figure 7.4. In each of the simulation runs, half of the sites present during a time period are randomly selected to serve as part of the training dataset of the model, while the remaining half serves as part of the testing dataset. In similar fashion, non-sites are randomly drawn from the non-site dataset, once to be part of the training data, and once again to become part of the testing data. The number of non-sites included is always equal to the number of sites.

The training data, comprising a random half of the site dataset and an equal number of randomly selected non-sites, is used to fit a binomial logistic regression model. The resulting coefficients can be used to assess the odds of predicting site presence when increasing the corresponding independent variable by one unit and keeping all other variables fixed, which will be explained here. In essence, the odds represent the ratio of the probability of the event occurring (i.e. site presence; p) and the probability of the event not occurring ($1 - p$; Eq. 7.1).

$$odds(success) = \frac{p}{1 - p} \qquad (7.1)$$

The probability of the event occurring ranges between 0 and 1, and the odds of that event occurring then range between 0 and infinity. The use of restricted ranges may cause problems when modelling a variable, and for this reason the odds are usually transformed to log-odds, which have a range between negative and positive infinity (Eq. 7.2).

$$\log(odds) = \log(\frac{p}{1 - p}) \qquad (7.2)$$

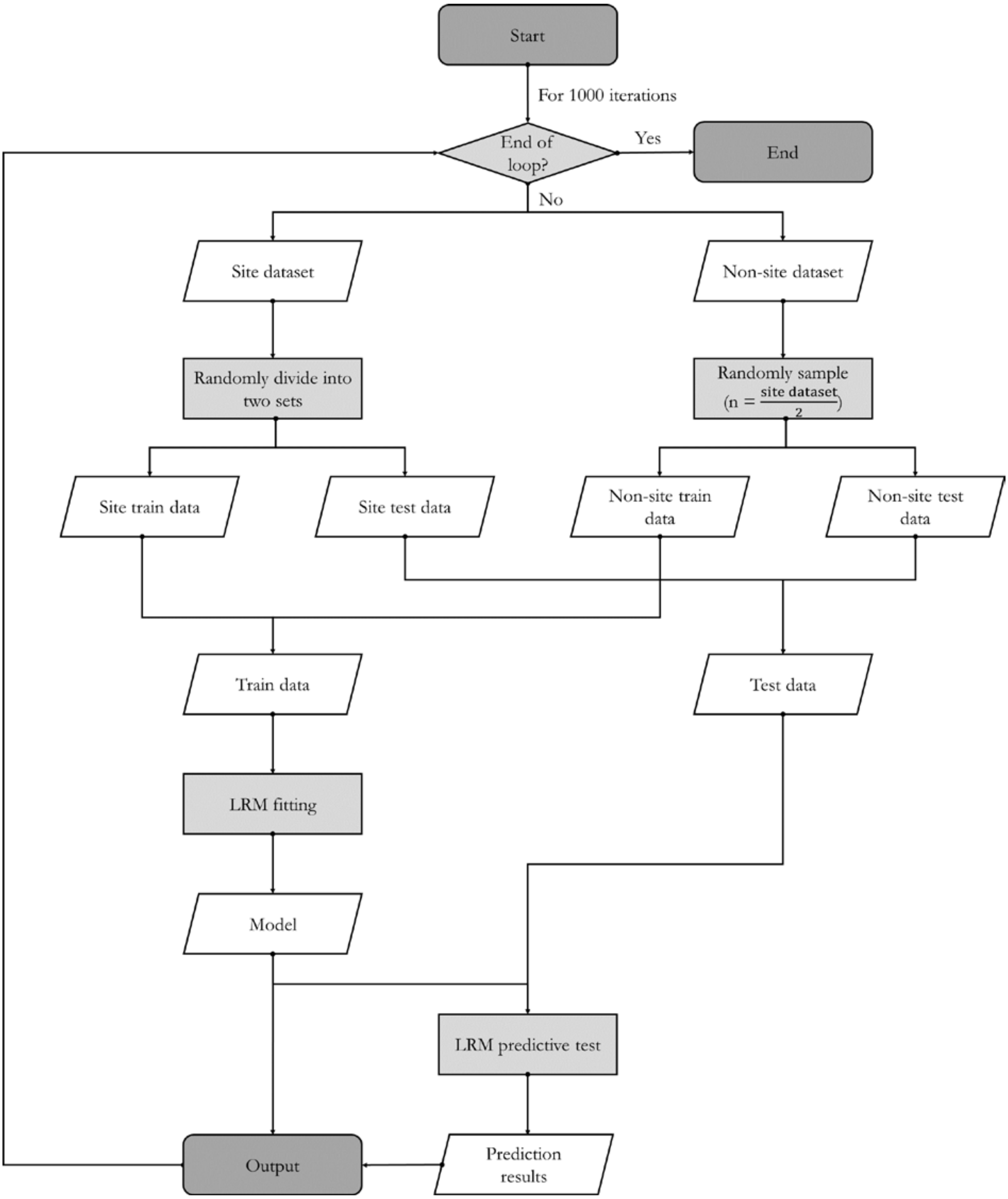


Figure 7.4. Flowchart of the multivariate analysis applied in this study.

The logistic regression model establishes a linear relationship (i.e. of the form $y = ax + b$) between the logit-transformed probability (probability of site presence; $\text{logit}(p)$) and the independent variables ($x_1, x_2, \dots, x_i$, representing the natural palaeogeography, distance to rivers and streams, etc.). The logistic regression analysis estimates parameter values (i.e. the coefficients; $a_0, a_1, a_2, \dots, a_i$) that fit the training data to the model (Eq. 7.3).

$$\text{logit}(p) = \log(odds) = a_0 + a_1 \times x_1 + a_2 \times x_2 + \cdots + a_i \times x_i \tag{7.3}$$

On the basis of the modelled Equation 7.3 the odds of the event occurring can be calculated by taking the natural number e to the power of the log-odds (Eq. 7.4).

$$odds = e^{\log(odds)} = e^{a_0 + a_1 \times x_1 + a_2 \times x_2 + \cdots + a_i \times x_i} \tag{7.4}$$

In similar fashion, when keeping all other variables fixed, the change in odds of predicting site presence when increasing an independent variable (e.g. x_1) follows Equation 7.5.

$$\Delta odds_{x_1} = e^{\log(a_1)} \tag{7.5}$$

The significance of the coefficients is tested using a Wald test (Wald 1943), that tests how well the model explains the training data without the variable, against how it does with that variable.

The next step is to assess the predictive capability of the fitted model. This is done using the testing data, consisting of the other half of the site dataset and again an equal number of randomly selected non-sites. For each point in the testing dataset, the probability that this point is a site location is tested with the model, resulting in a number between 0 and 1. In this study, 0.5 is used as a threshold, meaning that the model considers a point with a probability above 0.5 to be a site location and a point with a probability below or equal to 0.5 a non-site location. This can then be compared to the actual assignment to site/non-site categories, resulting in the 'accuracy' of the model (i.e. the relative amount of correct predictions).

The accuracy may be dependent on the split in the site dataset for the purpose of building the training and testing sets. While this can be considered circumvented through the Monte Carlo approach, there are alternative ways to measure the performance of the model. A typical way through which this is done is by plotting the ROC (receiver operating characteristic) curve and calculating the area under the curve (AUC). The ROC curve is a plot of the true positive rate against the false positive rate (i.e. the correct and incorrect predictions) at various probability thresholds. When the model has a good predictive ability, the AUC should be closer to 1 than it is to 0.5. As part of the output of this analysis, both the accuracy and the AUC are measured.

7.4 Results

7.4.1 Individual variable analysis

This section presents the results and an initial interpretation of the analysis of the individual variables. The extent to which these variables are important for settlement location in relation to each other is the goal of the multivariate analysis, presented in the following section 7.4.2.

7.4.1.1 Natural palaeogeography[2]

A cluster analysis was applied in order to examine the composition of the datasets, consisting of 500 m and 20 km radii around the 450 rural settlements included in this study.

For the 500 m radius, four clusters were identified (Table 7.5). The total mean silhouette was measured as 0.721, with the individual clusters ranging between 0.418 (cluster 2) and 1 (cluster 4). Excluding cluster 4, the mean silhouette would be 0.628. While slightly on the low side of clustering consistency, it is higher than other clustering solutions for this dataset. The low silhouette values may be the result of the relatively continuous nature of the landscape elements that are present in settlement location radii. Each of the identified clusters appears to represent a location typology where one individual palaeogeographic category is most prevalent, respectively 'sands and fluvial terraces', 'levees', 'floodplains', and 'peatlands'.

The clustering results for the 500 m radius are different from the one applied earlier on a dataset of 1088 rural settlements, where five clusters were identified (Verhagen *et al.* 2016b, 315). A separation was made between 'high levees' and 'low levees', whereas they are grouped into one 'levees' cluster in the current result, as becomes apparent in Table 7.6. Also interesting is that the original cluster 5 has largely disappeared, with only three of the original 28 settlements left as part of the 450 settlements included in this analysis. One remains identified as part of the 'peatlands' cluster, while two others have become part of the 'floodplain' cluster. Apparently these two settlements were more similar to those associated with floodplains than the remaining one, mostly associated with peatlands. The removal of such a large share of sites in the 'peatlands' cluster is a result of peatlands having a generally higher uncertainty sum. To a lesser extent this is also the case for the 'floodplains' cluster, which has two-thirds of its sites removed, while the other clusters have about half of their sites removed.

Cluster	1	2	3	4
Number of settlements	93	255	101	1
Percentage of settlements	20.7%	56.7%	22.4%	0.2%
High natural levees	2.6%	55.2%	16.8%	0%
Low natural levees	7.5%	36.2%	20.7%	0%
Floodplains	3.4%	6.3%	58.2%	0%
Peatlands	0.4%	0.1%	1.6%	68.5%
Sands and fluvial terraces	85.7%	0.8%	0.3%	30.3%
Fresh water	0.3%	1.4%	2.4%	1.2%
Sea and tidal flats	0%	0%	0%	0%

Table 7.5. Results of cluster analysis of palaeogeographic units, based on a 500 m radius around settlements.

[2] The content of this section is partly based on p. 314–16 of **Verhagen, P., I. Vossen, M. R. Groenhuijzen, and J. A. Joyce. 2016b. "Now You See Them, Now You Don't: Defining and Using a Flexible Chronology of Sites for Spatial Analysis of Roman Settlement in the Dutch River Area."** ***Journal of Archaeological Science: Reports*** **10: 309–21. doi: 10.1016/j.jasrep.2016.10.006.** Research design by PV, MG and JJ; data provided by PV, IV and MG; chronological reinterpretation by PV; case studies by PV and MG; discussion and conclusion by PV.

		Current clustering results				
		1	2	3	4	No longer part of dataset
Original clustering results	1	93	0	0	0	98
	2	0	185	0	0	229
	3	0	63	0	0	66
	4	0	7	99	0	220
	5	0	0	2	1	25

Table 7.6. Comparison of original clustering results on 1088 rural settlements (Verhagen et al. *2016b, 315) against current clustering results on 450 rural settlements for the 500 m radius.*

In the 20 km radius three clusters were identified (Table 7.7) with a total mean silhouette of 0.722, with the individual clusters ranging between 0.700 and 0.735. This can be considered a fairly consistent manner of clustering. The number and coverage of clusters is exactly the same as for the analysis applied on the dataset of 1088 settlements. Due to the much larger radius, the 20 km radius clusters appear to be a reduction to general landscape descriptions. This is evidenced by the spatial distribution of sites belonging to each cluster (Fig. 7.5). Sites are divided into an 'eastern river area' cluster which covers sandy areas and some broad levees, a 'central river area' cluster covering a landscape with large expanses of floodplain with broad levees and still some sandy areas, and a 'western river area' cluster covering a landscape of narrow levees with large expanses of peat. Similar to the findings of the 500 m radius, the amount of rural settlements removed after the reduction of the dataset to 450 settlements is greatest for the 'Western river area' cluster (87%, compared to 48% and 52% respectively for the other two clusters) because of the prevalence of peatlands in that area.

Cluster	1	2	3
Number of settlements	236	180	34
Percentage of settlements	52.4%	40.0%	7.6%
High natural levees	22.8%	19.0%	9.3%
Low natural levees	16.8%	14.6%	4.9%
Floodplains	11.3%	34.3%	23.5%
Peatlands	0.4%	9.7%	46.6%
Sands and fluvial terraces	47.0%	20.6%	8.2%
Fresh water	1.8%	1.8%	1.2%
Sea and tidal flats	0%	0%	6.2%

Table 7.7. Results of cluster analysis of palaeogeographic units, based on a 20 km radius around settlements.

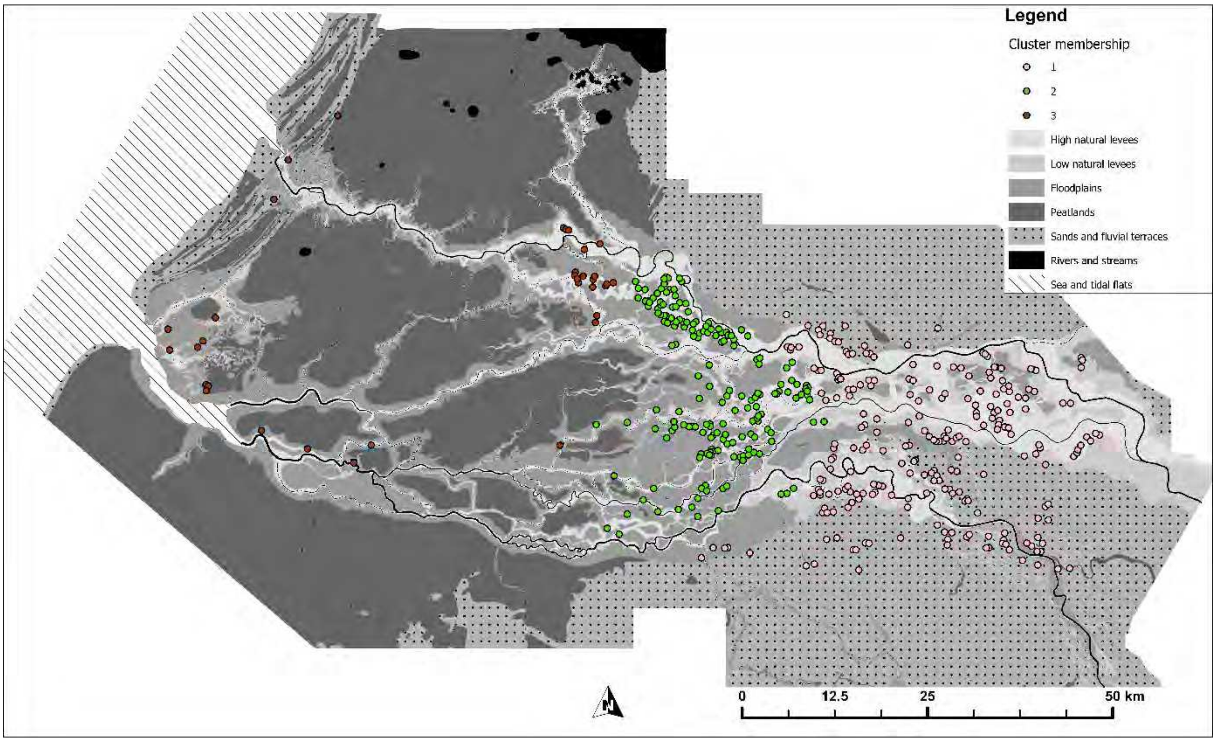


Figure 7.5. Spatial distribution of natural palaeogeography cluster membership of the 20 km radius clusters.

The information gathered in this analysis can be used to study changes in settlement location choices through time. When looking at the 500 m radius, the distribution of sites among the four clusters remains relatively stable (Fig. 7.6), although some notable differences can be observed. From the LIA up to the MRP A the proportion of settlements in cluster 3 rises while the one in cluster 2 falls. This is indicative of an increasing trend of settlements to be located closer to the edges of the 'marginal' floodplain, although the majority of settlements remain located more centrally on the levees. A similar pattern was observed in the dataset of 1088 settlements, meaning that it has not been altered by the reduction of the site dataset (Verhagen *et al.* 2016b, 315–16). This trend reverses from the MRP B towards to LRP B. The shift towards the floodplains can be explained in a number of ways, such as a move towards more animal husbandry as a mode of production, for which the floodplains may be more suitable, or simply a lack of suitable or available locations on the higher parts of the levees. The subsequent decline in settlement locations along the floodplain may then be explained by an increasing availability of land on the levees again (due to lower settlement densities).

For the 20 km radius, a clear difference in site proportions can be observed through time (Fig. 7.7). Initially, most settlements are in the eastern river area, but in the ERP B there is a sudden shift, with the central river area increasing in importance in terms of number of settlements. This implies that during the initial phase of increasing settlement density, the growth rate of the central river area was higher than that of the eastern river area. The eastern river area catches up with the central river area in the MRP A and slowly but increasingly becomes more important for settlement until the LRP A. These findings are not entirely similar to the results of the analysis on 1088 settlements, where it was found that the growth rate of the western river area was especially high from the ERP A until the MRP B (Verhagen *et al.* 2016b, 316). A similar conclusion cannot be reached in this analysis because the proportion of sites assigned to cluster 3 (the western river area) has decreased too significantly.

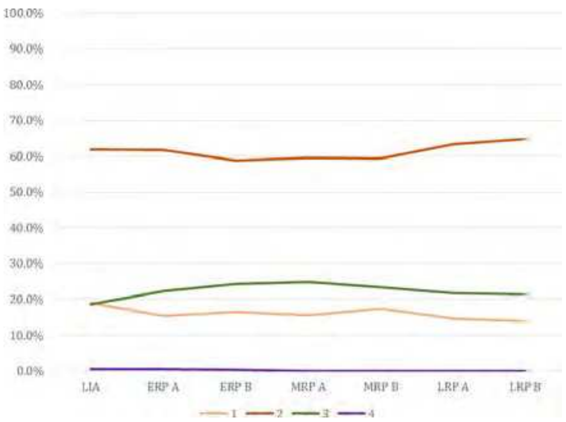


Figure 7.6. *Site cluster membership through time of the 500 m radius clusters.*

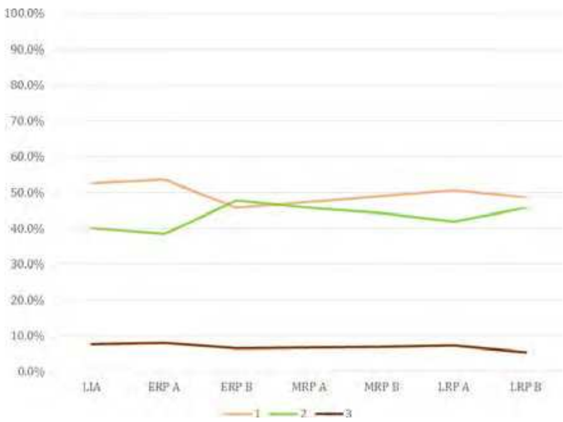


Figure 7.7. Site cluster membership through time of the 20 km radius clusters.

7.4.1.2 Rivers and streams

This analysis simply involved the calculation of the distance to the nearest river or stream for each of the 450 rural settlements. The general results are shown in Table 7.8.

Distance to nearest river or stream (m)	Number of settlements	Cumulative number of settlements	Cumulative % of settlements	Land area (km^2)	Cumulative land area (km^2)	Cumulative % of land area
0-100	30	30	6.7	*included		
100-250	30	60	13.3	*included		
250-500	41	101	22.4	1909.9*	1909.9	18.8
500-1000	64	165	36.7	1343.9	3253.7	32.1
1000-1500	65	230	51.1	1073.4	4327.1	42.7
1500-2000	67	297	66.0	883.7	5210.8	51.4
2000-2500	43	340	75.6	724.5	5935.3	58.6
2500-3000	36	376	83.6	594.1	6529.4	64.4
3000-3500	32	408	90.7	494.1	7023.5	69.3
3500-4000	14	422	93.8	393.0	7416.5	73.2
4000-4500	7	429	95.3	316.5	7733.0	76.3
4500-5000	7	436	96.9	269.0	8002.0	78.9
5000-5500	4	440	97.8	230.7	8232.7	81.2
5500-6000	4	444	98.7	202.4	8435.1	83.2
6000-6500	0	444	98.7	178.2	8613.3	85.0
6500-7000	2	446	99.1	158.0	8771.3	86.5
7000-7500	3	449	99.8	142.8	8914.1	87.9
7500-8000	0	449	99.8	124.6	9038.7	89.2
8000-8500	0	449	99.8	103.5	9142.3	90.2
8500-9000	1	450	100	89.9	9232.1	91.1
9000-9500	0	450	100	81.6	9313.7	91.9
9500-10000	0	450	100	72.7	9386.5	92.6
>10000	0	450	100	750.2	10136.7	100

Table 7.8. Number of rural settlements in intervals of distance to nearest river or stream and cumulative number of rural settlements within and closer than that interval, compared against the land area within those distances.

A substantial number of settlements, more than 22%, are within 500 m of the nearest river and stream. This is slightly higher than would be expected based on the amount of land area that are within that distance, which is almost 19%. However, the discrepancy between land area and settlements within a certain distance interval to rivers and streams becomes greater for higher distance values, with a maximum reached at the 3000-3500 m interval. Almost 91% of the 450 rural settlements analysed are within 3500 m of the nearest river or stream, whereas only 69% of land area is within that distance. The vast majority of settlements are within 6000 m of the nearest river or stream (compared to 83% of land area), with only six outliers being further away. This suggests that there is a certain tendency for habitation to be near rivers or streams, but they do not necessarily have to be within a very short distance (e.g. within 500 m).

It is interesting to see if any trends can be witnessed through time. After splitting the analysis results between time periods, the distance to nearest river or stream is plotted in Figure 7.8. All time periods show a similar pattern, with a large number of settlements being within 2000 m of the nearest river or stream, and a sharp decline in the number of settlements in subsequent distance intervals.

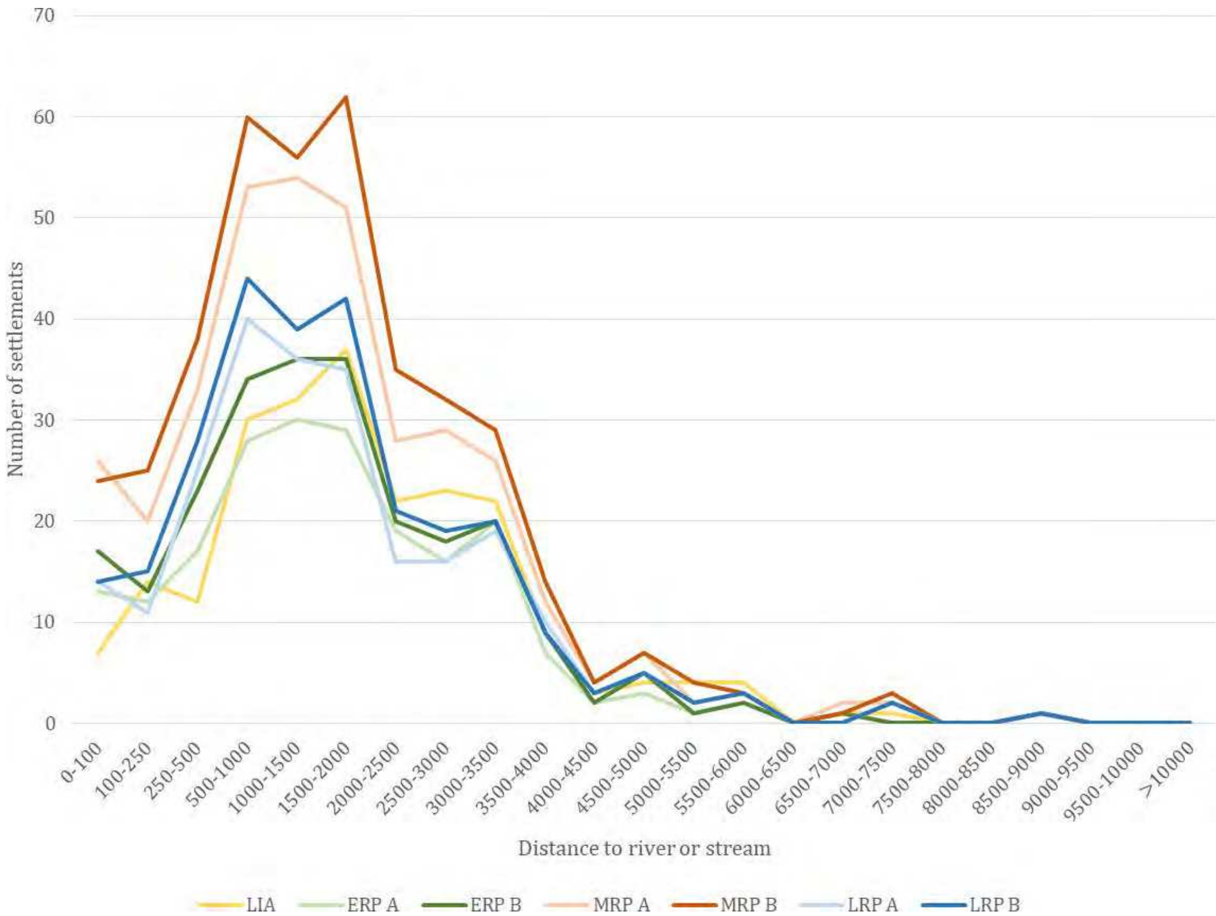


Figure 7.8. Distribution of settlements over categories of distance to nearest river or stream, separated per time period. Absolute values are shown instead of percentages so that the individual plots and general trends are more easily distinguished.

In terms of percentage, the largest difference is between the LIA and the later time frames. Only 58% of settlements are within 2000 m of a river or stream in this time period, with the second-lowest, the ERP A, having 64% within that distance. In comparison, the variety between the various time frames of the Roman Period is within 4 percentage points. The latter is true for most distance intervals, suggesting that there is no significant change in settlement location preferences with respect to the distance to rivers and streams throughout the Roman Period. Given that the dataset for the LIA is not complete (mostly including sites only when they are continuous into the Roman Period; see also section 3.3), it is also not possible to use this information as an indication of changing location preferences regarding distance to rivers and streams from the Late Iron Age to the Roman Period.

7.4.1.3 Forts

In order to shed light on the relation between rural settlement location and the location of the Roman military forts, an analysis was performed to find the distance of each settlement in a certain time period to the nearest fort of the preceding time period. Table 7.9 shows the results, firstly separated per time period, and secondly split between settlements that were already existing in the previous time period (thus considered contemporary to the forts to which the distance is calculated) and settlements that newly appear in the time period under study (whose location is possibly influenced by the location of the already existing forts).

The results show that in the ERP B and the MRP A, new settlements tend to appear closer to the forts of the preceding period than the already existing settlements. The reverse is true for the MRP B and the LRP B. However, the application of a Student's t-test shows that the difference between the means of the two populations (new and existing settlements) is not significant for any of the time periods. Because there are no new settlements appearing in the LRP A within the current dataset of 450 rural settlements, this measure could not be performed for this time period.

Even though the difference between the average distance to forts is not statistically significant, it may be useful to get an idea of where exactly new settlements appear throughout time with respect to the location of the previously existing forts. This attribute differs from the measurements above, because it looks at the difference between the four sets of newly appearing settlements across time periods rather than between the two sets of settlements (newly appearing and existing) within one time period. A comparison between these sets is shown in Figure 7.9.

Time period	Settlements	Number of settlements	Average distance to nearest fort (m)	Difference between new and existing settlements	P-value
ERP B	New settlements	38	12874	-1665	0.3559
	Existing settlements	200	11209		
MRP A	New settlements	130	8476	-773	0.2064
	Existing settlements	223	7703		
MRP B	New settlements	55	7600	143	0.8603
	Existing settlements	343	7743		
LRP A	New settlements	0	n/a	n/a	n/a
	Existing settlements	238	7655		
LRP B	New settlements	34	14113	772	0.6686
	Existing settlements	233	14885		

Table 7.9. Average distance of rural settlements per time period to the nearest fort of the preceding time period, separated between new settlements and settlements that already existed in the preceding time period, and the P-value of a Student's t-test for H_0: $\mu_1 = \mu_2$.

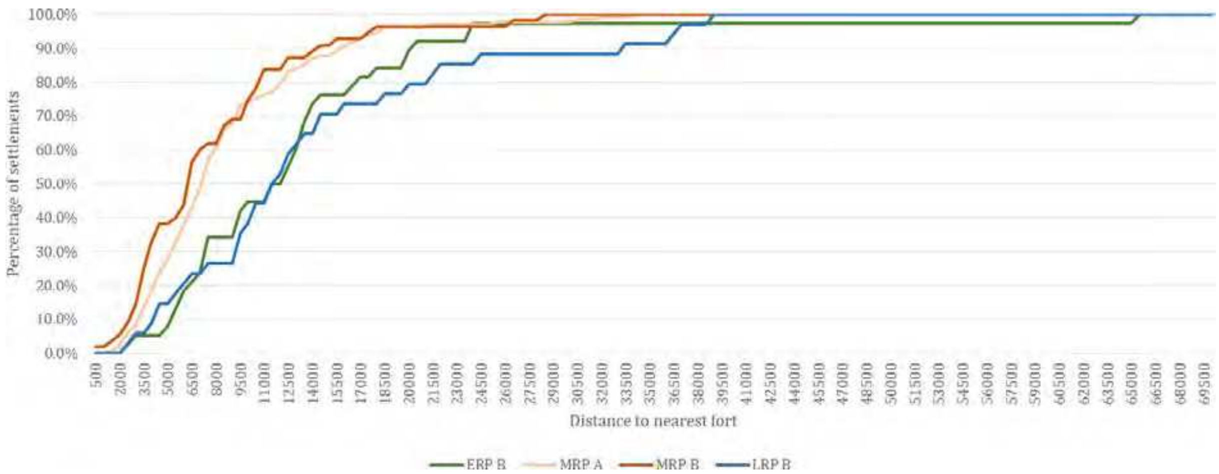


Figure 7.9. Cumulative percentage of newly appearing settlements within a certain distance to the nearest fort, separated per time period.

The first remarkable characteristic about this figure is that although all plots appear to roughly follow an inverse function, the steep initial slope does not start at a distance to the nearest fort of 0. Over all time periods, there is a total of two settlements that newly appear within 1 km of a fort, and five more that appear between 1 and 2 km of a fort. All eight of these new appearances within 2 km of a fort occur in the MRP A or MRP B. All other newly appearing settlements in all time periods are at a minimum distance of 2 km away from the nearest fort. Since the distance is measured towards the point locations of the forts, the size of the fort itself and the presence of a possible *vicus* has to be taken into account (since there is no space for a rural settlement there). Nonetheless, it can be said that newly appearing settlements tend to stay away from the immediate vicinity of the Roman military forts. The same conclusion was found by Weaverdyck (2018) in his multivariate analysis of the Dutch *limes* area in which forts functioned as potential markets.

Furthermore, the plots in Figure 7.9 show a difference between settlements that newly appear in the MRP A or MRP B and settlements that newly appear in the ERP B or LRP B. In the MRP A and MRP B, 80% of settlements appear within 12 and 11 km of forts respectively, whereas for the ERP B and LRP B this number is only reached within 17 and 21.5 km respectively. This difference can largely be attributed to the number of forts available; in the preceding time periods of the MRP A and MRP B (the ERP B and MRP A) the Roman *limes* along the Rhine was fully developed, whereas in the ERP A not all forts were yet constructed, and in the LRP A many forts were abandoned. For these reasons, it is not possible to substantiate a difference between time periods for the location of newly appearing settlements in relation to forts.

7.4.1.4 Transport networks

To study the relation between settlements and transport networks, the distance of newly appearing settlements to the pre-existing transport network was calculated. The average results are shown in Table 7.10. The results when splitting the data into 500 m intervals and a comparison against the total amount of land area within that distance of the modelled transport network of the preceding period are shown in Figure 7.10.

Figure 7.10 shows that there is a strong tendency for new settlements to appear close to the transport network of the preceding period. Between 55% (ERP A) and 71% (MRP B) are within 500 m of the already existing network, while only between 11% (ERP A) and 15% (LRP A) of the available land area is within that range. Barring a few exceptions, all new settlements appear within 5 km of the already existing network, even though that only covers roughly 50% of the total land area. The tendency of archaeological sites to appear in the vicinity of transport networks was also found by Van Lanen *et al.* (2015, 156) in their research on interregional transport corridors in the Roman and Early Medieval Periods.

Time period	Number of newly appearing settlements	Average distance to network (m)
ROMVA	82	709
ROMVB	38	624
ROMMA	130	660
ROMMB	55	505
ROMLA	0	n/a
ROMLB	34	442

Table 7.10. Average distance of newly appearing rural settlements per time period to transport network of the preceding time period.

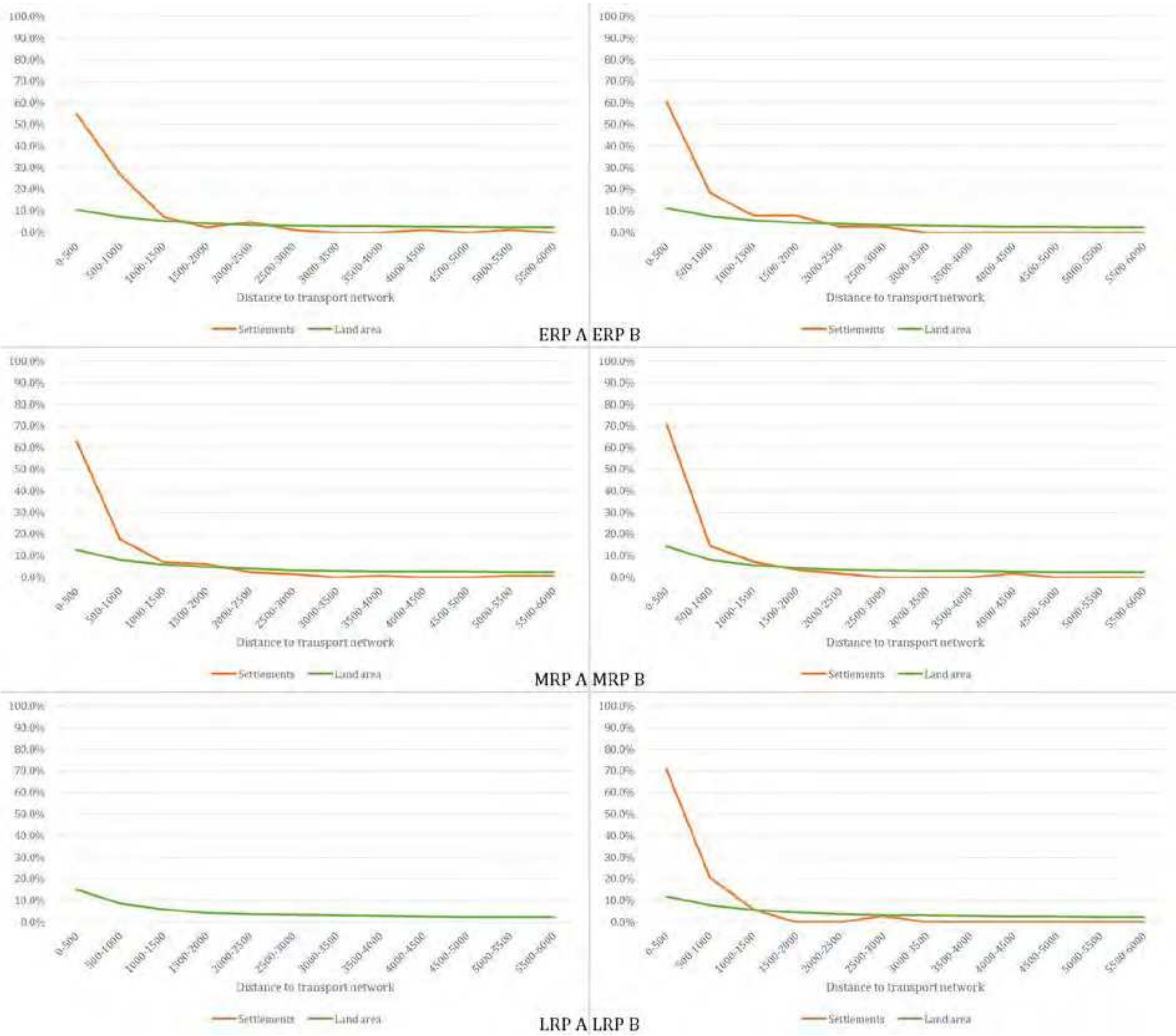


Figure 7.10. Percentage of new settlements per interval of shortest distance to transport network, compared against the percentage of land area within that distance interval.

Comparing between time periods, the MRP B and LRP B have the strongest tendency of settlements to be close to the preceding network, while this is weakest for the ERP A. This is partly the result of the size of the network of the preceding period; the LIA network is smaller (as a result of a smaller site dataset) than that of the MRP A. However, this is not the case for example for the LRP A network, but the new settlements of the LRP B are still for 71% within 500 m of the network. This indicates that the size of the network is not the only explanation for a higher tendency of settlements to be within short distance of that network; the network seems to be an attracting factor for new settlement locations. Taking into account the effect of differences in network size, the attraction of the network appears to be relatively strong in the ERP B and the LRP B, and less so in the MRP A.

7.4.1.5 Intermediary sites in transport networks

Similar to the analysis of site location in relation to forts, the analysis of site location in relation to potential intermediary sites in transport networks is performed by calculating the distance between the settlements and the selected intermediary sites. The results are shown in Table 7.11.

Time period	Settlements	Number of settlements	Average distance to nearest fort (m)	Difference between new and existing settlements	P-value
ERP A	**New settlements**	82	5584	-433	0.5818
	Existing settlements	119	5151		
EPR B	**New settlements**	38	5644	-490	0.4917
	Existing settlements	200	5155		
MRP A	**New settlements**	130	5362	-601	0.2008
	Existing settlements	223	4761		
MRP B	**New settlements**	55	4281	118	0.8213
	Existing settlements	238	7655		
LRP A	**New settlements**	0	n/a	n/a	n/a
	Existing settlements	238	3979		
LRP B	**New settlements**	34	5447	-902	0.1800
	Existing settlements	233	4545		

Table 7.11. Average distance of rural settlements per time period to the nearest potential intermediary site of the preceding time period, separated between new settlements and settlements that already existed in the preceding time period, and the P-value of a Student's t-test for $H_0: \mu_1 = \mu_2$.

It is found that new settlements generally tend to appear further away from the existing potential intermediary sites than the settlements that are continuous from the preceding time period. This is the case for new settlements in the ERP A, ERP B, MRP A and LRP B. Only in the MRP B, new settlements appear slightly closer to the existing intermediary sites than the settlements already present. The LRP A could not be analysed since no new sites appear in this period among the 450 settlements that are part of this analysis. However, a Student's t-Test shows that the difference between the datasets of new and existing settlements is not significant for any of the time periods. In general, there is a decreasing trend in distance to the existing potential intermediary sites from the ERP B until the LRP A. However, this can mostly be attributed to the increasing number of intermediary sites over the ERP A-MRP B timespan.

It is possible that there is a difference between regions. Weaverdyck (2018) in his multivariate analysis of the Dutch *limes* area included the market potential of a number of large civil settlements, partly corresponding to the intermediary sites used here, as an independent variable. His analysis distinguished between the central and the eastern river area, and found that for the eastern river area, proximity to such 'market centres' was an important factor for settlement, and that intermediary sites potentially played an important role in the socio-economic structure of the region was also argued earlier here in the study of local transport networks in section 6.4.3.

7.4.1.6 Historical landscape

The analysis of the relation between the historical landscape and settlement locations was done following the methodology presented in Nuninger *et al.* (2016) and Verhagen *et al.* (2016a). For each time period, a heritage map was calculated that represents the intensity of occupation in previous periods. The heritage values range from no heritage (0) to very high heritage (4). The results are shown in Table 7.12. In this table, Kvamme's gain (Kvamme 1988, 329) is used as a measure of the strength of location preference for each heritage value. Kvamme's gain is measured as 1 – settlements expected (%)/settlements observed (%), with the percentage of expected settlements based on the available land area. A value of 0 thus means that the number of observed settlements is equal to the expectation based on an equal distribution of the settlements over the available land area. All values above 0 indicate that the amount of observed settlements is higher than the expectation (i.e. more attractive for settlements), and values below 0 indicate that it is lower than expected (i.e. less attractive for settlements).

Heritage value		0	1	2	3	4
ERP A	New settlements	45	11	11	12	3
	New settlements (%)	54.88	13.41	13.41	14.63	3.66
	Land area (%)	95.17	1.22	1.21	1.20	1.21
	Kvamme's gain	-0.73	0.91	0.91	0.92	0.67
ERP B	New settlements	9	1	5	14	9
	New settlements (%)	23.68	2.63	13.16	36.84	23.68
	Land area (%)	93.83	1.57	1.53	1.53	1.54
	Kvamme's gain	-2.96	0.40	0.88	0.96	0.94
MRP A	New settlements	44	5	8	41	32
	New settlements (%)	33.85	3.85	6.15	31.54	24.62
	Land area (%)	93.51	1.64	1.62	1.61	1.62
	Kvamme's gain	-1.76	0.57	0.74	0.95	0.93
MRP B	New settlements	18	2	9	8	18
	New settlements (%)	32.73	3.64	16.36	14.55	32.73
	Land area (%)	92.17	1.96	1.96	1.95	1.95
	Kvamme's gain	-1.82	0.46	0.88	0.87	0.94
LRP A	New settlements	0	0	0	0	0
	New settlements (%)	n/a	n/a	n/a	n/a	n/a
	Land area (%)	91.72	2.09	2.07	2.05	2.06
	Kvamme's gain	n/a	n/a	n/a	n/a	n/a
LRP B	New settlements	0	0	0	8	26
	New settlements (%)	0	0	0	23.53	76.47
	Land area (%)	92.15	1.98	1.95	1.97	1.95
	Kvamme's gain	n/a	n/a	n/a	0.92	0.97

Table 7.12. Number and percentage of newly appearing settlements per heritage value, compared against total land area with that heritage value.

The results show that there is a strong preference for settlements to be located in areas with a high heritage value. In all periods, the areas with a heritage value of 0 have a lower number of new settlements than would be expected based on the available land area with that heritage value. This effect is least strong in the ERP A, with a relatively large number of new sites in the areas of no (0) heritage, as well as relatively high numbers in areas with low (1) to medium (2) heritage, and a relatively low number of new sites in areas of very high heritage (4). This may point to a tendency of new settlements in the ERP A to stay further away from the LIA settlement locations, as is suggested also on the basis of archaeological research (e.g. De Bruin 2017 for the Cananefatian *civitas*). However, part of the effect may be caused by a relative lack of heritage through the exclusion of data prior to the LIA. From the ERP B onwards, the highest Kvamme's gain scores are in the areas of high (3) and very high (4) heritage, with medium (2) heritage slightly behind. In areas of low (1) heritage the number of new settlements is still higher than expected on the basis of the available land area, but relatively low compared to the other areas.

The results can possibly be influenced by the filtering of the site dataset for spatial uncertainty on the basis of uncertainty in the palaeogeographic map (section 7.2.2). This excluded a large number of sites, while the above analysis does not exclude the correspondent areas of uncertainty. A correction for this can be made by calculating the number of expected settlements on the basis of the areas with an average uncertainty value smaller than or equal to 1, rather than on the basis of the entire study area. The results are shown in Table 7.13.

Heritage value		**0**	**1**	**2**	**3**	**4**
ERP A	**New settlements**	45	11	11	12	3
	New settlements (%)	54.88	13.41	13.41	14.63	3.66
	Land area (%)	93.44	1.53	1.58	1.65	1.80
	Kvamme's gain	-0.70	0.89	0.88	0.89	0.51
ERP B	**New settlements**	9	1	5	14	9
	New settlements (%)	23.68	2.63	13.16	36.84	23.68
	Land area (%)	91.65	1.96	2.00	2.14	2.25
	Kvamme's gain	-2.87	0.25	0.85	0.94	0.91
MRP A	**New settlements**	44	5	8	41	32
	New settlements (%)	33.85	3.85	6.15	31.54	24.62
	Land area (%)	91.29	2.04	2.11	2.20	2.36
	Kvamme's gain	-1.70	0.47	0.66	0.93	0.90
MRP B	**New settlements**	18	2	9	8	18
	New settlements (%)	32.73	3.64	16.36	14.55	32.73
	Land area (%)	89.57	2.39	2.54	2.66	2.84
	Kvamme's gain	-1.74	0.34	0.84	0.82	0.91
LRP A	**New settlements**	n/a	n/a	n/a	n/a	n/a
	New settlements (%)	n/a	n/a	n/a	n/a	n/a
	Land area (%)	89.00	2.55	2.65	2.79	3.01
	Kvamme's gain	n/a	n/a	n/a	n/a	n/a
LRP B	**New settlements**	0	0	0	8	26
	New settlements (%)	0	0	0	23.53	76.47
	Land area (%)	89.56	2.40	2.51	2.69	2.85
	Kvamme's gain	n/a	n/a	n/a	0.89	0.96

Table 7.13. Number and percentage of newly appearing settlements per heritage value, compared against total land area with that heritage value and average uncertainty ≤ 1.

As is shown, calculating the number of expected settlements on the basis of the entire land area rather than just the land area with average uncertainty equal to or smaller than 1 does not substantially change the outcome. Using just the relatively certain areas, the Kvamme's gain values are smoothed slightly, but still the areas with no (0) heritage have a notably lower amount of new settlements. There is a generally strong tendency for new settlements to appear in areas of high (3) or very high (4) heritage. This tendency is less strong for the ERP A (fewer in the very high category) and MRP B (slightly fewer in the high category than in the medium category), but still the number of new settlements is higher than would be expected on the basis of the available land area.

7.4.2 Multivariate analysis

Using a Monte Carlo approach, a logistic regression model was repetitively fitted to a training dataset that consisted of half of the sites present during a certain time period, plus an equal number of randomly selected non-site locations. The model was subsequently tested using a testing dataset, consisting of the other half of the present sites and another set of randomly selected non-site locations. Initially, the independent variables under consideration were the natural palaeogeography (500 m clusters), distance to rivers and streams, distance to forts, distance to transport networks, distance to potential intermediary sites and the historical landscape. In most cases these relate to the elements present in the preceding time period, and therefore the LIA does not include the historical landscape or the distance to forts, intermediary sites and transport networks, since there is no preceding time period. The ERP A does not include the distance to forts, since there are no forts in the preceding LIA. The average resulting coefficients (over 1000 runs), corresponding P-values and the accuracy and AUC values of the model are given in Table 7.14.

	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
	Coefficients						
Intercept	-0.040	1.526	1.012	0.300	0.198	-7.7E+14	-2.1E+14
Intermediary sites		-5.6E-05	-2.7E-04	-6.6E-05	-1.6E-04	4.1E+09	1.0E+09
Forts			1.8E-04	5.2E-05	8.8E-05	-1.2E+09	6.2E+08
Transport networks		-5.8E-04	-1.2E-03	-5.5E-04	-1.1E-03	-1.8E+10	-7.3E+08
Rivers and streams	-1.6E-04	-4.6E-04	-1.4E-03	-2.5E-04	-3.3E-04	1.6E+09	1.7E+09
Historical landscape		1.056	5.289	1.060	1.421	3.6E+14	8.2E+13
Palaeogeography 2	2.238	0.442	-11.461	0.186	-1.087	-1.6E+14	-1.7E+13
Palaeogeography 3	0.527	-0.055	-8.067	-0.400	-1.497	-1.3E+14	-1.2E+13
Palaeogeography 4	-10.679	-9.248	-18.984	-16.792	-15.914	2.59E+13	-1.4E+12
	P-values						
Intercept	0.595	0.254	0.475	0.508	0.499	0.697	0.551
Intermediary sites		0.406	0.416	0.308	0.148	0.697	0.635
Forts			0.430	0.337	0.224	0.693	0.694
Transport networks		0.078	0.173	*0.025	0.089	0.688	0.710
Rivers and streams	0.125	0.104	0.277	0.238	0.192	0.695	0.693
Historical landscape		*0.010	*0.005	*0.000	*0.000	0.696	0.515
Palaeogeography 2	*0.000	0.459	0.311	0.512	0.305	0.698	0.741
Palaeogeography 3	0.338	0.525	0.314	0.475	0.209	0.698	0.742
Palaeogeography 4	0.508	0.705	0.743	0.989	0.991	0.695	0.936
Accuracy	0.774	0.892	0.951	0.911	0.948	0.983	0.978
AUC	0.857	0.961	0.987	0.976	0.988	0.985	0.989

Table 7.14. Average coefficients and corresponding P-values for a logistic regression model for each time period, and the accuracy and AUC values of the model. P-values indicated with an asterisk (*) are considered significant ($P \leq 0.05$).

As was detailed in section 7.3.2, the coefficients in Table 7.14 give an indication of the relationship between the independent variable and the dependent variable (i.e. site presence or absence). They can be transformed to a change in odds of site presence when increasing that independent variable by one unit (and keeping all other variables fixed) by taking e to the power of the coefficient (see Eq. 7.5). The P-values give an indication of how significant these coefficients are, based on a Wald test. This test examines how well the model explains the training data without the variable, against how it does with that variable. P-values ≤ 0.05 are considered significant, meaning that the absence of these parameters would significantly alter the outcome of the model. The accuracy values represent how well the model based on the training dataset explains the testing dataset. High values thus mean that the model was highly able to distinguish between locations of site absence and site presence. Finally, AUC is another method to measure the performance of the model, based on the ratio between correct and incorrect predictions.

It becomes readily clear that the values for the LRP A and LRP B are not very trustworthy. The coefficients are much larger than is seen in other time periods, indicating that a small change in any variable has a large impact on the prediction of site presence. Furthermore, none of the coefficients has a consistently significant impact on the model as a whole judging by the P-values. Looking at individual runs, the historical landscape is a significant parameter in a number of runs in the LRP B (but only rarely in the LRP A). This lack of significant coefficients apparently does not detriment the predictive capability of the model: the average accuracy and AUC are very high, indicating that the model produces a good result. The model is good at discriminating between site and non-site locations, but likely only for the specific training and testing datasets that are used. The fact that all sites of the LRP A already exist in the preceding MRP B may also play a role for this period. Some of the factors thus become irrelevant: the distance to transport networks is always 0 and the heritage values are always high. This cannot be the only explanation however, since this is not the case for the LRP B.

For the ERP A, ERP B and MRP B time periods, the only significant coefficient is the historical landscape. On the basis of this coefficient it can be said that sites are more likely to be located in areas with high heritage values: a one unit increase in heritage value increases the odds of site presence in the ERP A by 2.9 ($e^{1.056}$; e to the power of the coefficient, see Eq. 7.5), and in the ERP B by as much as 198.1 ($e^{5.289}$). In the MRP A period, besides the historical landscape the distance to the existing transport network also becomes significant. Here it is found that sites are more likely to be located close to the transport network of the preceding time period: a one unit distance increase changes the probability of site presence by 0.9988 ($e^{-1.2\times10^\wedge-3}$). This may seem relatively small, but it is a greater decrease in probability than for other time periods. It must also be considered that the distance is measured in metres. The equivalent change in probability per 1000 units of increase (i.e. one kilometre) is 0.3012, which means that for each kilometre closer to the transport network the probability of site presence is over three times greater.

Although the natural palaeogeography is not considered a significant coefficient in any time period, it is still interesting to look at the relative proportions of each cluster. It is found that sites tend to avoid cluster 4 (peatlands-dominated), and to a lesser extend cluster 3 (floodplains-dominated). This is true for ERP A, MRP A and MRP B. Interestingly, in the ERP B sites apparently also avoid cluster 2 (levee-dominated), suggesting that sites strongly prefer the sandy areas. This may be the result of the filtering of the site dataset, potentially resulting a large loss of sites in the levee-areas during the ERP B. For the entire ERP-MRP timeframe, the accuracy and AUC are high, indicating that the model is good at discriminating between site and non-site locations.

The LIA differs from the other time periods because this period cannot rely on the historical landscape or the preceding transport network as independent variables. Here the only significant coefficient is found to be the Palaeogeography 2 dummy variable, corresponding to the natural palaeogeographic cluster 2 (levee-dominated). Archaeological sites are 9.4 ($e^{2.238}$) times more likely to be located on levees in the LIA than on the sandy areas (the reference cluster). The predictive ability of the model is less than that of other time periods, but it still performs reasonably well in discriminating between sites and non-sites.

In general it can be stated that the historical landscape has been the most important factor for many of the time periods, with the exception of the LIA (which could not include this variable) and the LRP A and LRP B (which did not result in any significant coefficient). It can even be argued that the historical landscape is such a dominating factor that it obscures the possible importance of other parameters. For example, the majority of sites in the LRP A and LRP B have heritage values of 4, whereas only 10% of non-site locations even exceed a heritage value of 0. For this reason it may be interesting to repeat the analysis with the exclusion of the historical landscape as an independent variable. The results are shown in Table 7.15.

	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
	Coefficients						
Intercept	-0.022	2.555	4.217	2.586	3.217	2.8E+13	2.978
Intermediary sites		-2.0E-05	-3.9E-05	-1.1E-04	-7.5E-05	-1.4E+09	-7.1E-05
Forts			-7.1E-06	5.5E-05	1.4E-05	3.4E+08	2.5E-05
Transport networks		-1.4E-03	-3.2E-03	-1.4E-03	-3.7E-03	-1.1E+10	-5.3E-03
Rivers and streams	-1.7E-04	-2.8E-04	-3.1E-04	-1.9E-04	-1.7E-04	-2.2E+07	-1.4E-04
Palaeogeography 2	2.220	0.616	-0.568	0.421	-0.073	2.7E+13	0.687
Palaeogeography 3	0.517	0.038	-1.008	-0.242	-0.567	1.1E+13	-0.015
Palaeogeography 4	-10.730	-9.202	-9.408	-16.859	-15.590	-3.8E+13	-14.806
	P-values						
Intercept	0.586	*0.048	*0.010	*0.003	*0.001	0.922	*0.027
Intermediary sites		0.415	0.447	0.074	0.299	0.914	0.367
Forts			0.497	0.319	0.516	0.908	0.475
Transport networks		*0.000	*0.000	*0.000	*0.000	0.836	*0.000
Rivers and streams	0.122	0.219	0.248	0.272	0.311	0.906	0.445
Palaeogeography 2	*0.000	0.406	0.467	0.426	0.516	0.940	0.389
Palaeogeography 3	0.349	0.523	0.361	0.503	0.427	0.944	0.514
Palaeogeography 4	0.509	0.669	0.685	0.988	0.989	0.925	0.992
Accuracy	0.772	0.883	0.911	0.887	0.920	0.977	0.934
AUC	0.856	0.940	0.968	0.952	0.975	0.978	0.980

Table 7.15. Average coefficients and corresponding P-values for a logistic regression model for each time period excluding the historical landscape as independent variable, and the accuracy and AUC values of the model. P-values indicated with an asterisk (*) are considered significant (P ≤ 0.05).

With the exclusion of the historical landscape, other variables now become more important to the model. Most obviously, the distance to transport networks has become a very significant parameter in the model for predicting site presence. Sites tend to strongly concentrate in the vicinity of the transport network of the preceding time period during the ERP A, ERP B, MRP A, MRP B and LRP B, with the rate of change per unit change being between 0.9963 (for the MRP B) and 0.9986 (for both the ERP A and MRP A). The LRP A still has the same characteristics as in the model with the historical landscape variable: the coefficients are very sensitive and although the average accuracy appears high, that is probably only the case for the specific training and testing datasets used in each run.

Another factor that becomes significant during the same time periods is the intercept of the logistic regression model (i.e. the a_0 in Eq. 7.3). While it is difficult to draw conclusions on the basis of this, it is relevant to note that with the creation of the dummy variables of natural palaeogeography, the natural palaeogeographic cluster 1 is essentially captured in this constant in order to function as a reference point to the dummy variables representing clusters 2, 3 and 4.

The significant intercept might thus indicate a tendency of sites to be located on cluster 1 (sandy areas and fluvial terraces), and the coefficients further indicate that sites tend to avoid cluster 4 (peatlands) and to a lesser extent cluster 3 (floodplains). In contrast, during the LIA cluster 2 is significant: the probability of site presence on levees is found to be 9.2 ($e^{2.220}$) times higher than that of site presence in sandy areas, as was found in the earlier analysis as well.

The previous tests have constructed a logistic regression model on the basis of the entire site dataset. A relevant split that can be made is between sites that are already present during a time period, and sites that newly appear in a time period. The analysis on new sites has also been performed previously in the individual variable analysis, and will be repeated here. A main obstacle in this exercise is that it is difficult to say how 'correct' the model actual is, since the testing dataset becomes very small. A special case is the LRP A, which in the current dataset does not contain any sites that are not already present in the preceding MRP B. Furthermore, this analysis was not performed for the LIA, since all sites can be considered newly appearing sites and the model thus does not differ from the previous one. The results are presented in Table 7.16.

	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
	Coefficients						
Intercept		6.022	152.102	1.699	55.708		-90.386
Intermediary sites		-2.1E-04	-4.3E-03	-1.0E-04	-3.8E-03		1.1E-03
Forts			1.1E-03	7.3E-05	1.4E-03		7.9E-05
Transport networks		-9.4E-04	-0.040	-5.8E-04	-0.011		-5E-05
Rivers and streams		-1.1E-03	-0.019	-2.8E-04	-0.011		-1.2E-03
Historical landscape		2.088	47.319	1.007	22.981		40.357
Palaeogeography 2		0.696	-86.316	0.201	-23.335		-8.733
Palaeogeography 3		0.543	-115.244	-0.420	-25.994		-19.108
Palaeogeography 4		-15.092	-25.706	-17.607	-16.841		-20.962
	P-values						
Intercept		0.098	0.694	0.238	0.307		0.977
Intermediary sites		0.401	0.757	0.306	0.429		0.976
Forts			0.762	0.349	0.554		0.977
Transport networks		0.159	0.709	0.051	0.446		0.978
Rivers and streams		0.145	0.724	0.309	0.467		0.977
Historical landscape		0.504	0.674	0.059	0.325		0.969
Palaeogeography 2		0.505	0.746	0.520	0.536		0.981
Palaeogeography 3		0.511	0.758	0.469	0.483		0.981
Palaeogeography 4		0.994	0.973	0.992	0.993		0.987
Accuracy		0.884	0.817	0.857	0.846		0.930
AUC		0.941	0.865	0.936	0.911		0.959

Table 7.16. Average coefficients and corresponding P-values for a logistic regression model for newly appearing sites in each time period, and the accuracy and AUC values of the model.

The average accuracy and AUC of the models are slightly lower than that of the same analysis on the complete dataset (Table 7.14), but can still be considered high. None of the coefficients is found to be significant, but there are some that appear to have a relatively large impact on the model. Especially in the ERP B, MRP B and LRP B the historical landscape has a very strong influence on the prediction of site presence: the change in probability per unit increase ranges between 9.6×10^{-9} and 9.6×10^{-20} for these time periods. Another strong predictor is again the distance to transport networks, which is almost a significant coefficient in the MRP A. For the ERP B the rate of change per unit increase is 0.9603 ($e^{-0.040}$) which is lower than that of any other distance to transport network coefficient in the previous analyses. However, especially noteworthy is the coefficient for distance to the nearest river or stream: it follows a similar pattern as the distance to transport networks, with periods of strongest attraction in the ERP B and MRP B, but with a stronger coefficient for all periods. In the analysis of all settlements the reverse was the case, and it can thus be said that besides the historical landscape the location of newly appearing settlements is both influenced by distance to transport networks and distance to rivers and streams, with the latter having a slightly stronger attraction than the former. The dependence on the relatively small testing datasets becomes clear when looking at the factors of natural palaeogeography: from the ERP A until the MRP B there is an alternation between site attraction and strong site repulsion for cluster 2 (levees), which can only be logically explained by the use of the small dataset.

Concluding the results with some general statements on the multivariate approach to site location, it is found that in most models the historical landscape is a strong predictor for site presence. This may be partly grounded in truth, but will also be the result of the rules on which the non-site location dataset was constructed: non-sites of a specific time period were not allowed to appear within 500 m of sites that exist in that period. For this reason and because of the strong dominance of the historical landscape, the model was redone using all independent variables except the heritage. Here it was found that the distance to transport networks is often the next best predictor for site presence. This is not very surprising for sites that continue from the preceding time period, since they are already a node in the transport network. However, a similar conclusion was drawn from the analysis on only newly appearing sites. It can thus be said that new settlements are found to be preferentially located on or close to existing transport routes.

7.5 Discussion

This section will discuss the findings from the previous sections: what narrative can be written from the settlement location analysis applied in the form of an individual variable analysis and a multivariate analysis on the filtered dataset of 450 rural settlements in the Dutch part of the Roman *limes*? Firstly, a point has to be made about the dataset itself. The chronological and spatial filtering was applied according to transparent rules, although it must be said that these rules remain arbitrary, as the rule parameters can in principle be varied with and possibly lead to different results. The filters applied in this study led to a dataset that strongly focussed on the eastern part of the Rhine-Meuse delta: only a few sites remained in the western half of the study region. This inevitably led to a bias in the results as well, as was found for example in the analysis of the natural palaeogeography (section 7.4.1.1), where a comparison with an earlier study (with a larger unfiltered site dataset) showed that the 500 m cluster analysis produced a different amount of clusters with different relative sizes. It must be realised then that any results produced in these analyses will only be able to shed light on settlement location preferences in the eastern half of the study area, and are not readily applicable on the western half.

Looking at the variables under consideration, it is interesting to note that the largest roles are played by the historical landscape and the distance to rivers and streams and to the transport networks of the preceding period. Further interesting conclusions can be derived from the natural palaeogeography, as will be illustrated further below. Of lesser importance were the distance to forts and the distance to potential intermediary sites in transport networks, which were not found to have a significant impact on predicting settlement presence or absence in the logistic regression model. In fact, Weaverdyck (2018) even found that the forts to some extent repelled settlements (i.e. settlements were less likely to be found in close proximity to the fort), consistent with his earlier research on the Danube region (Weaverdyck 2016), and which was also proposed above in section 7.4.1.3. Apparently, settlement location was primarily determined by the location in the natural environment and the location within the rural social landscape.

For the LIA, only a few variables were available that could be used to analyse settlement location. The multivariate analysis found cluster 2 of the natural palaeogeography to have the highest impact on the probability of settlement presence. This is confirmed by the individual variable analysis, where more than 60% of settlements are found to be part of cluster 2 (dominated by levees), with the remainder relatively evenly split between cluster 1 (dominated by sandy areas) and cluster 3 (dominated by floodplains). It is not possible to compare these findings to any preceding periods since they are not included in this study, but they can serve as a baseline against which the younger periods can be compared.

The ERP A is the first period for which elements of the preceding period (the LIA) can be used. Besides the natural palaeogeography and distance to rivers and streams, the ones incorporated here are distance to transport networks, distance to potential intermediary sites in transport networks and the historical landscape. For the entire dataset, the multivariate analysis found that the historical landscape is the most significant factor for the probability of settlement presence. It could be said that settlements in the ERP A tend to be in (the vicinity of) areas that were already inhabited in the preceding LIA. This remains true when only looking at the location of newly appearing settlements (i.e. sites not present during the preceding LIA), although it was no longer found to be significant in the logistic regression model. When excluding the historical landscape as a factor, the distance to the transport network of the LIA was found to be another important and significant factor in determining site location. Looking only at the newly appearing settlements, the distance to rivers and streams was slightly more important than the distance to the transport network. The natural palaeogeography was not found to be a significant factor, but the individual variable analysis found that in general from the LIA to the ERP A there was a shift in settlement location preference from the sandy areas to the more marginal floodplain-dominated areas, with the levee-dominated areas remaining the most preferred habitation area at a constant level.

The results for the ERP B are fairly comparable to those of the ERP A. The historical landscape was found to be the most important factor in the multivariate analysis for determining the probability of settlement presence. In the individual variable analysis, it was found that the ERP A had a stronger preference for the areas with very high (4) heritage, while the ERP B had a strong preference for both areas with very high (4) and high (3) heritage. This may point to a shift in settlement location to areas that are more marginal to the already existing settlement landscape. After the historical landscape, the transport network is again the second-most important factor for the whole settlement dataset of the ERP B. Looking only at newly appearing settlements, the distance to rivers and streams is slightly more important than the distance to transport networks, but both seem to have played a role in determining settlement locations. Looking at the individual palaeogeographic analysis, a further shift in settlement location occurs, with the relative amount of settlements in the floodplain-dominated areas increasing at the expense of those in the levee-dominated areas. This does not mean that the number of settlements in the latter area are declining, but rather that the growth in the number of settlements in the floodplain areas is increasing. Similar to what was found for the historical landscape, this may point to a shift in settlement location preference to the more marginal areas. There are multiple possible explanations for such a shift, such as a move towards more animal husbandry as a mode of production, for which the floodplains may be more suitable, or simply a lack of suitable or available locations on the higher levees.

The logistic regression model of the MRP A again has the historical landscape as the most significant factor in the probability of settlement presence. However, even in the presence of the historical landscape variable, the distance to the transport network of the preceding period now also becomes a significant factor. It is also close to being significant when only considering newly appearing settlements. This may be stated as remarkable, since the individual variable analysis of distance to transport networks (section 7.4.1.4) found that the attraction of the transport network was least strong for the MRP A. That it is found as such a significant factor can thus only be explained as being the result of the relatively large size of the transport network, making it 'easier' for settlements to be within close range of it. Looking at the natural palaeogeography, the relative amount of settlements in the floodplain-dominated areas reaches its maximum in the MRP A, although the relative amount on the levees also slightly recovers, both at the expense of the relative amount of settlements on the sandy areas. The shift towards more marginal locations, as already argued above, was also seen by Weaverdyck (2018) in his multivariate analysis of the Dutch *limes* area, and argues that the shift towards different modes of production (e.g. animal husbandry) is a more likely explanation than population pressure on the basis that the number of settlements on the levees still increases in the MRP B.

The MRP B is not remarkable in that the historical landscape is again found to be the most influential factor in determining settlement presence. Looking at the individual variable analysis however, it is interesting to note that a relatively large number of new settlements appear in areas of medium (2) heritage. Compared to the preceding MRP A and ERP B, which had a strong preference only for the areas of high (3) and very high (4) heritage, this points to a further shift towards the margins of the settlement landscape. Looking at the natural palaeogeography, this appears to coincide with a small shift towards the sandy areas, and a relative decline in the amount of settlements in the floodplains. It can thus be concluded that the marginal areas to which the settlements shift is mostly found in the sandy areas, rather than in the floodplains, which was the case for the ERP A-ERP B shift. This could possibly be the result of the Rhine-Meuse delta becoming 'full', hardly leaving any room for new habitation on the levees and floodplains, at least in the eastern part of the delta. It is further supported when looking at the 20 km radius clusters in the individual analysis of the natural palaeogeography (section 7.4.1.1), where a steady (proportional) shift from the 'central' to the 'eastern' river area is present during the ERP B-LRP A interval, i.e. a shift from a levee/floodplain environment to a levee/sandy area environment. The distance to the transport network is another important aspect for settlement location, and the individual variable analysis of this factor showed that the MRP B has one of the strongest attractions for new settlements, indicating that new settlements tend to appear on or near existing routes between other settlements.

The LRP A is characterised by a marked decline in the number of settlements compared to the MRP B, and it would be interesting to see if there are any notable changes in settlement location preferences. Unfortunately, this is partly hindered by the lack of settlements that can be said to newly appear in the LRP A within the filtered dataset used in this study. Furthermore, the logistic regression failed to produce a consistent model across the various runs. Statements can thus only be made with the knowledge that all LRP A settlements under consideration were already existing in the MRP B, and only on the basis of the analyses of the individual variables. Looking at the natural palaeogeography, there is a marked relative increase in settlements in the levee-dominated areas. This does not indicate a growing number of settlements, but rather that the decline is less strong in the levee area than in the floodplain area or sandy area. Considering that the latter two served as 'marginal' areas where new settlements shifted towards to in the ERP A-ERP B interval and in the MRP A-MRP B interval, the shift in the opposite direction can be interpreted as an abandonment of these 'marginal' areas.

The final period under consideration the LRP B, has a slightly growing number of settlements, meaning that there are also newly appearing settlements that can be studied separately again. The historical landscape is again found to be the most important factor for these newly appearing settlements, although the distance to rivers and streams and the transport network also play a role. Looking at the individual variable analysis, the attraction of the transport network was fairly strong during the LRP B compared to the other time periods, especially when considering the relatively small size of the network in this time period. This indicates that the new habitation tends to be located within the existing habitation areas rather than along the margins, which was seen in the earlier ERP A-ERP B and MRP A-MRP B shifts. This case is strengthened when looking at the individual analysis of the natural palaeogeography, which shows that there is no shift towards the floodplain-dominated and sandy area-dominated clusters. What occurs is rather the opposite: the focus of settlement on the levees that was initiated in the MRP B-LRP A shift is continued in this time period.

7.6 Conclusion

This chapter aimed to study settlement location preferences through an analysis of the individual variables that potentially influenced site location, as well as through a multivariate approach in which these variables are studied in conjunction. It was found that the historical landscape and the distance to the transport network were important factors for settlement location, showing that the inclusion of cultural/social factors such as the historical landscape as well as modelled transport networks has a valuable impact on such a settlement location study. In terms of results, some interesting shifts were found in settlement location preferences through time, with a shift towards more 'marginal' areas in the ERP A-ERP B and MRP A-MRP B intervals, in terms of both the natural environment as well as the settlement landscape. This may for example be explained as the result of changing modes of production or as a result of increasing pressure in the core habitation area on the levees. The opposite was seen in the LRP A-LRP B shift, where new settlements were primarily located within the core habitation area rather than along the margins, perhaps because the relatively low population density did not necessitate such a move.

8 Synthesis[1]

8.1 Introduction

8.1.1 General introduction

The main aim of the 'Finding the limits of the *limes'* project is to reconstruct and understand the cultural landscape of the Dutch part of the Roman *limes* and its hinterland, specifically looking at the spatial and economic interactions between the Roman military population and the local population. The spatial component is evidently an important part of the research project, and the palaeogeographic analysis of the Dutch *limes* area thus became the main focus of this dissertation. The general aim of this study was to reconstruct and analyse the cultural landscape of the Dutch *limes* area using computational approaches; more specifically it models and analyses transport networks, settlement patterns and includes their relationship with the natural environment.

This chapter will present the general results of this part of the project, and place it in the wider research context. It aims to showcase some of the innovative aspects of the study, either from technical, methodological or interpretative viewpoints. To do this, case studies presented in this study in the realm of transport networks and settlement location in the Dutch part of the Roman *limes* are utilised. The questions that form the basis of these case studies are: how were goods transported from the local population to the military population, and what is the role of stone-built rural settlements in these transport networks; can location preferences shed light on the interaction between the local population and the military population?

Formulated in a more general question, the goal of this chapter is as follows: what has this spatial analytical study of the cultural landscape of the Dutch *limes* area contributed to the research field of computational archaeology and related fields, and what has it contributed to the archaeological understanding of the Dutch part of the Roman *limes*?

8.1.2 Palaeogeographic analysis of the Dutch *limes* area

The palaeogeographic analysis of the Dutch part of the Roman *limes* that is performed as this PhD-study within the context of the 'Finding the limits of the *limes*' project can be subdivided in three parts: firstly, a reconstruction of the natural palaeogeography of the Rhine-Meuse delta in the Roman period; secondly, a reconstruction and analysis of local transport networks; and thirdly, an analysis of settlement location in the landscape. This section provides a summary of these three branches of the study, with more elaboration on the analyses and results and their place in the wider research context presented in the following sections.

In order to understand spatial developments and patterns in the cultural landscape in relation to the natural landscape, the natural landscape must be accurately known first. There is a strong tradition of reconstructing the natural environment in the Netherlands (e.g. Cohen *et al.* 2012; Vos

[1] The content of this section was published earlier in slightly modified form as **Groenhuijzen, M. R. 2018b. "Palaeogeographic Analysis Approaches to Transport and Settlement in the Dutch Part of the Roman *Limes*." In P. Verhagen, J. A. Joyce, and M. R. Groenhuijzen (eds.) *Finding the Limits of the* Limes*. Modelling Economy, Demography and Transport on the Edge of the Roman Empire*. Simulation Studies in Archaeology. Cham: Springer**, the only difference being a small addition to the conclusion and minor rephrasing.

2015), and for the Roman period a great advance was made following the study of Van Dinter (2013) on the Old Rhine area between Utrecht and Katwijk. Using a similar methodology, this study has extended the 1:50,000 reconstruction of Van Dinter to cover the entire Rhine-Meuse delta, the geographic area roughly equal to what is considered the Dutch part of the Roman *limes*.

Transport as part of the cultural landscape is often understudied in archaeology, both due to the focus on settlements in archaeology and due to the immaterial nature of transport, particularly that of transport on the local scale. However, when we are interested in the interaction between the local and the Roman military population, most transport occurs on the local scale. In this research, computational modelling approaches are used to study local transport networks. A least-cost path (LCP) approach is applied to reconstruct local transport connections (e.g. Groenhuijzen and Verhagen 2015), and concepts of network science and formal network analysis are applied to reconstruct and analyse local transport networks (e.g. Groenhuijzen and Verhagen 2016; 2017). The resulting networks are used to study archaeological questions such as the provisioning of the Roman military population from the local population and the potential role of intermediary sites in such provisioning networks. A significant part of the PhD-study was focussed on local transport networks, and this aspect thus serves as the largest contribution to this chapter.

The study on the location of settlements in the landscape has had a traditional following in processual archaeology and predictive modelling (e.g. Brandt *et al.* 1992; Verhagen 2007). Most focus has traditionally been on site location in the natural landscape, but other aspects may also have played a role, among them (distance to) forts, transport networks, and the influence of the historical landscape (e.g. Nuninger *et al.* 2016). This study has used a multivariate approach (e.g. Stančič and Veljanovski 2000; Fernandes *et al.* 2011; Weaverdyck 2018) to find how these various factors determined the location of rural settlements.

8.2 Natural palaeogeography

The Rhine-Meuse delta in the Netherlands is a highly dynamic region, and the modern landscape is hardly a representative of the Roman landscape. To reconstruct the natural palaeogeography of the Dutch part of the Roman *limes*, a methodology was adopted from Van Dinter (2013; Chapter 2). For the central part of the Dutch *limes* area this involves the manual combination of various source datasets in a GIS, ranging from geomorphological maps, soil maps, elevation maps, earlier palaeogeographic reconstructions and data from archaeological research. For the eastern part of the study area this methodology is less applicable because the corridor through which the Rhine and Meuse move is narrower here, resulting in more erosion and burial of older channel belts. Therefore, a simple overlay of the existing geomorphological and palaeogeographic maps was used. The reconstructed natural palaeogeography represents the landscape roughly around AD 100 (Fig. 8.1).

From a technical and methodological point of view the reconstruction of the natural landscape for archaeological analysis is not innovative. A number of palaeogeographic datasets were already developed in the Netherlands, but they are often either on a coarse (1:500,000) national scale (e.g. Vos and De Vries 2013) or on a local scale (e.g. Vos and Gerrets 2005; Cohen *et al.* 2009), sometimes focused on particular geomorphological elements rather than the landscape as a whole. Van Dinter (2013) provided a reconstruction that is suitable for the required level of analysis at the local and regional level, which is why this methodology was also used for extending the reconstruction to encompass the entire Dutch *limes* area.

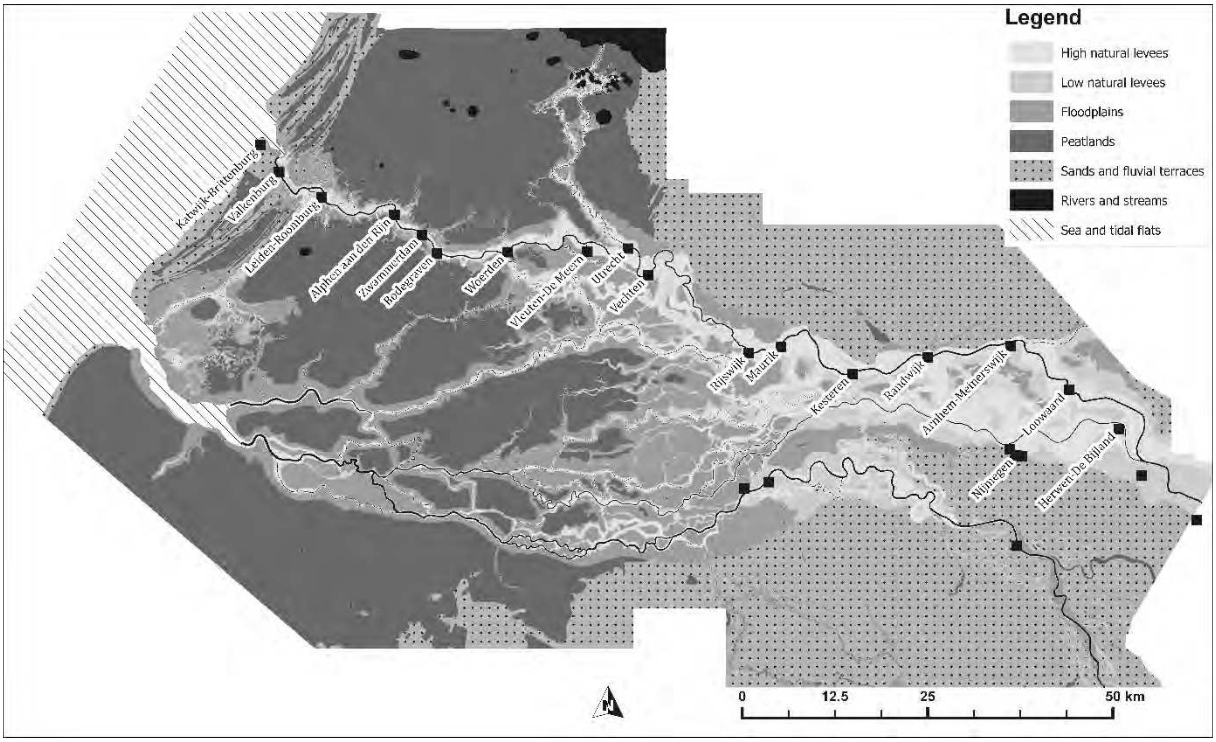


Figure 8.1. Natural palaeogeographic reconstruction (simplified) with diachronic overview of Roman fort locations.

Large yet detailed palaeogeographic reconstruction allow for analyses of archaeological phenomena on unprecedented scale. Examples include the reconstruction of transport connections (Chapter 5; Groenhuijzen and Verhagen 2015; Van Lanen *et al.* 2016), the modelling of agricultural production (Van Dinter *et al.* 2014; Joyce 2018) and site location analysis (Verhagen *et al.* 2016b; Chapter 7). The value of such reconstructions for archaeological research has become more prominent in the Netherlands in recent years, also outside the 'Finding the limits of the *limes*' project (e.g. Pierik 2017; Van Lanen 2017; De Kleijn 2018).

An additional advantage to performing the detailed palaeogeographic reconstruction in a GIS is the ability to incorporate other information alongside the reconstruction. One important factor which is often overlooked in analyses using reconstructed landscapes is the uncertainty of the reconstruction itself. For the Rhine-Meuse delta, such uncertainty can come from post-Roman fluvial erosion, drift sand activity, peat reclamation or excavation, and anthropogenic developments. By mapping the sources of uncertainty, a cumulative uncertainty map can be generated that can be used in further analyses (Fig. 8.2), for example to filter the site dataset to only include those for which the palaeogeographic information is relatively certain, as has been done for the settlement location analysis (Chapter 6).

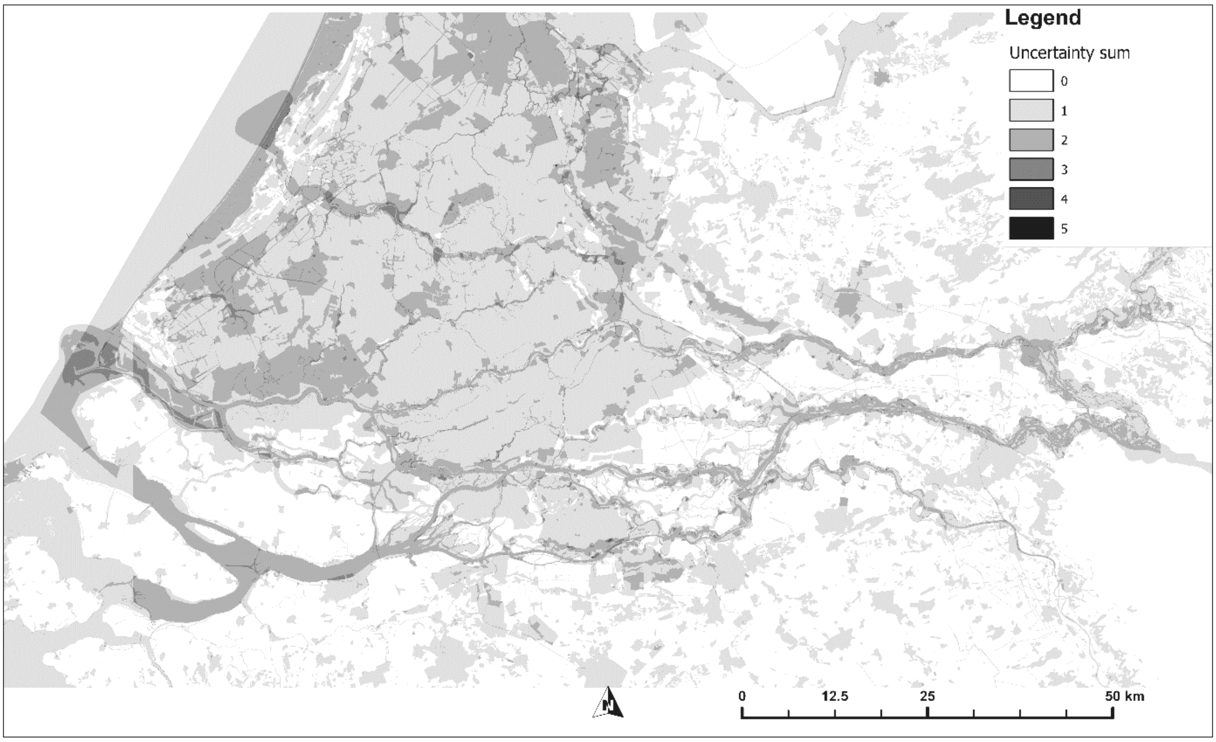


Figure 8.2. Cumulative uncertainty map associated with the natural palaeogeographic reconstruction.

8.3 Transport networks

8.3.1 Introduction

The study of mobility and transport in the Roman period has traditionally been focussed on the regional to empire-wide scale, and particularly on shipping in the Mediterranean and on the military road networks, including that in the Netherlands (e.g. Scheidel 2014; Van der Heijden 2016). In comparison, fairly little research has been done on transport on the local to intraregional scales, mainly due to the lack of archaeologically visible local road systems.

In order to bridge this gap of knowledge, computational approaches have become increasingly popular, and the basic parameters of movement are rather well understood (Murrieta-Flores 2010; Polla and Verhagen 2014). Most computational approaches apply least-cost path (LCP) modelling, since this method allows for the incorporation of various cost components, for example regarding ancient topography. However, until recently most applications of LCP modelling in the study of movement have been done to reconstruct single routes or small sets of routes, or to identify the factors involved in establishing routes (e.g. Bell and Lock 2000; Llobera 2000; Zakšek *et al.* (2008); Verhagen 2013). The majority of LCP studies utilises elevation/slope as the main component and only models walking (Herzog 2014a), and there are many functions available to do this analysis (Herzog 2013d). Applications that use other cost components are sparse, however (e.g. Livingood 2012; Verhagen 2013), as is the application of LCP modelling on other modes of transport (e.g. Wheatley and Gillings 2002; Verhagen *et al.* 2014).

Networks have become a common concept in archaeology, and over the last decade the use of network science in computational archaeology has grown in popularity (Brughmans 2013a). The formal study of sets of LCPs as networks however has thus far only been explored in a limited way, even though the application of formal network analysis techniques has shown to offer additional information that cannot be deduced from LCP maps qualitatively (e.g. Verhagen *et al.* 2013a).

8.3.2 Modelling transport

In order to study transport in the Dutch *limes* area, transport connections between all settlements were modelled in Python using a LCP approach (Chapter 5). Since the Rhine-Meuse delta has fairly little topographical relief, the impact of terrain conditions on movement is more important than that of slope. The formula (Eq. 8.1) modified from Pandolf *et al.* (1977) allows for the calculation of walking speed (V in m/s) while incorporating the walker's weight (W in kg), carried load (L in kg), standard metabolic rate (M in W) and the natural terrain through a terrain coefficient (η), with the coefficients provided by Soule and Goldman (1972). LCPs could thus be modelled using the reconstructed natural palaeogeography, resulting in a more accurate representation of local transport in the Dutch *limes* area (Groenhuijzen and Verhagen 2015; sections 5.3.1-5.3.2).

$$V = \sqrt{\frac{M - 1.5W - 2.0(W + L)(\frac{L}{W})^2}{1.5\eta(W + L)}} \tag{8.1}$$

Furthermore, the Pandolf *et al.* (1977) formula allows for the incorporation of varying weights of the carried load. It was found that this has a significant impact on how people could move through the landscape and particularly the time it takes to move. In general, movement with animal-drawn carts is slower and less forgiving for difficult terrains, which results in different properties of the transport networks that were constructed afterwards (Groenhuijzen and Verhagen 2015; section 5.3.3).

Besides walking, other modes of transport must also have played a role in the local transport system of the Dutch *limes* area. Animal-drawn carts were modelled using LCPs, with the costs based on functions provided by Raepsaet (2002). The modelled routes tend to avoid the wetter parts of the landscape, with most movement occurring on the higher and drier levees (section 5.4.1).

Little is known about local-scale transport infrastructure, likely largely due to the immaterial nature of the routes (Willems 1986). However, a comparison with the known infrastructure, namely the military road along the Rhine, is possible. Interestingly enough, a comparison of the modelled routes with an archaeological reconstruction of the road and potential secondary routes in the direct hinterland (Vos 2009) shows that the modelled routes largely concentrate outside the military road, and actually quite closely align with the assumed secondary routes (Fig. 8.3). Based on the LCP analysis performed in this study, the conclusion can be drawn that the military road thus seems to be largely peripheral to the majority of local-scale interactions (Groenhuijzen and Verhagen 2015; section 5.4.1).

In addition to land-based transport modes, the local and military population also made use of water-based transport options, as has been attested by a number of dugouts and larger river ships that have been found in the research area (e.g. Jansma and Morel 2007). This study has modelled dugouts as the main representative of water-based transport on the local scale using experimental data (Gregory 1997). One of the problems when modelling water-based transport using a LCP approach is that in reality it is not possible to easily transfer between land- and water-based modes, and it is probably not possible at every location along a waterway. It is largely unknown where potential transfer places in the Rhine-Meuse delta would be, which means that the routes modelled through LCP analysis may not be the most realistic (sections 5.3.4 and 5.4.2).

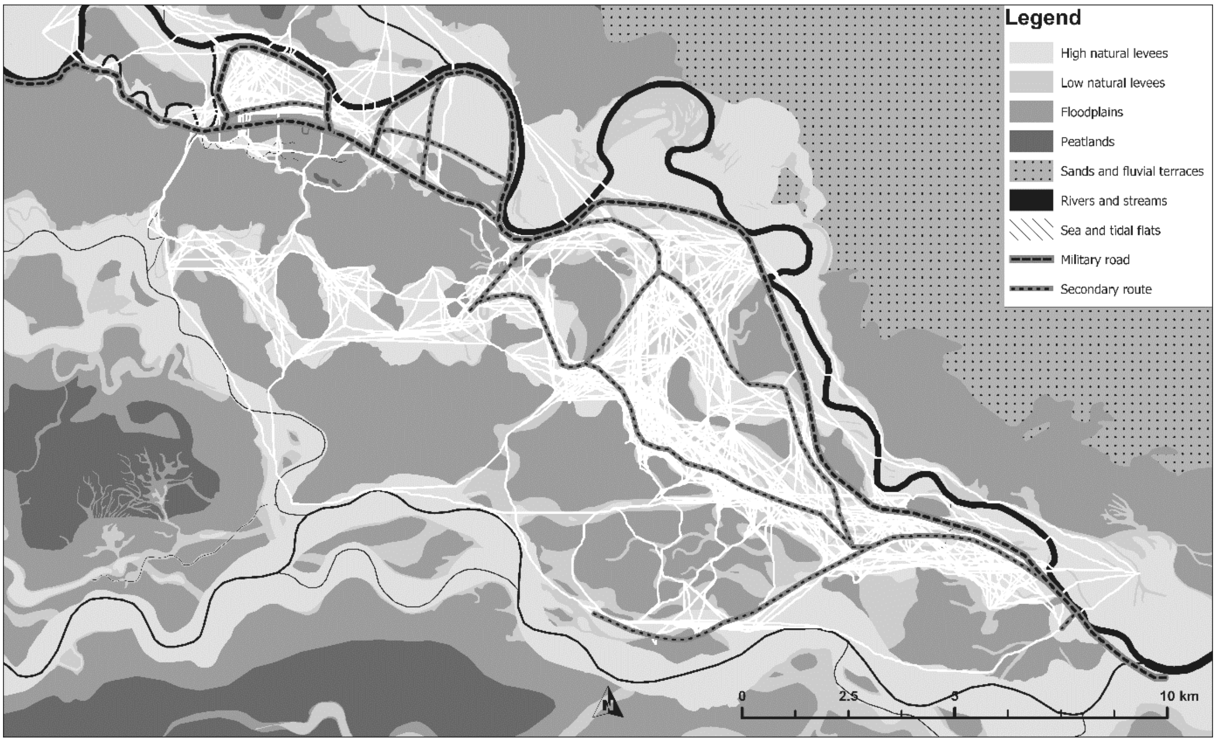


Figure 8.3. Comparison of ox-cart based transport connections modelled through LCP analysis (white lines) with the archaeological reconstruction of the military road and possible secondary routes (Vos 2009).

Through modelling multimodal routes between settlements in the research area (combining land- and water-based transport) it was found that some routes preferred waterways over land-based routes, but the majority of movement still followed the levees rather than water. This is likely due to the location of rivers: they are largely peripheral to local scale transport, and flow in an east-west direction, whereas a fair share of movement is south-north directed (or vice versa), particularly when moving from settlements in the hinterland towards the forts along the Rhine (section 5.4.2).

In general, the modelling of local transport connections through a LCP approach in this PhD study was successful in terms of understanding the interaction between movement and the natural environment. However, the modelling of movement on foot remains more reliable than the of animal-based or water-based transport modes. The former has a stronger tradition in physiological and archaeological research, whereas animal- and water-based transport models have to rely on fewer and less compatible sources to the situation of the Dutch Rhine-Meuse delta (e.g. in terms of terrain factors for carts or the influence of rivers on dugouts). The modelling of alternative means of transport thus remains a valuable avenue for future research.

8.3.3 Constructing networks

Modelled local transport connections do not readily tell anything about the functioning of transport in the Roman period, for example regarding questions such as the movement of surplus production from the rural settlements to the Roman military population. In order to address such questions, an additional step has to be undertaken to convert the dataset of transport connections modelled through LCP analysis into local transport networks.

However, earlier LCP network studies have given little thought to the choice of network structure (Herzog 2013a; 2013b). Rivers *et al.* (2013) argue this choice must be based on the suitability for the archaeological record that the network structure aims to represent. To address this, a comparison was made between network construction techniques with the aim to find the best representation of a local provisioning system that connects the rural settlements to the Roman military population in the forts (Groenhuijzen and Verhagen 2017; section 6.2).

The network construction techniques compared were maximum distance networks, proximal point networks, a Delaunay triangulation, a Gabriel graph (Gabriel and Sokal 1969) and efficiency networks (Fulminante *et al.* 2017). The networks were evaluated on the criteria that all forts have a sufficient amount of settlements connected to it (either directly or indirectly), that the network does not contain too many connections, and that the forts are relatively easily accessible so that provisioning could be carried out relatively efficiently. The latter was measured through 'local' average path length, which is the average path length calculated from a limited number of nearest settlements to each fort. It was found that the Gabriel graph was the best representation of a local transport network functioning as a provisioning system connecting the rural settlements to the forts (Fig. 8.4; Table 8.1). It had a relatively low 'local' average path length without creating too many connections. It was matched by some proximal point networks, but only for those that had an unrealistically high number of neighbours, and the Delaunay triangulation, which was disregarded on the basis of the inclusion of a number of unrealistic long-distance connections.

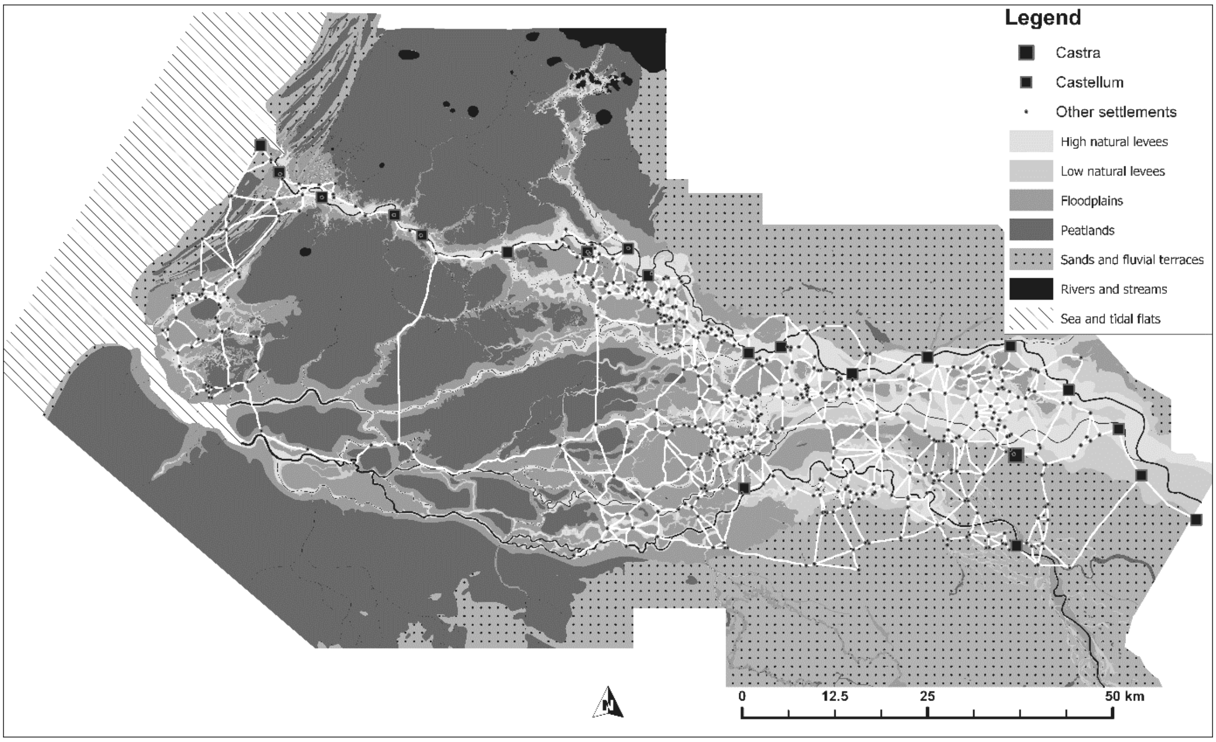


Figure 8.4. Gabriel graph network of transport connections modelled through LCP analysis (white lines), based on walking while carrying a load of 20 kg in the Middle Roman Period A.

Besides finding a network structure that best represents a local transport network for the Dutch *limes* area, this study has confirmed the position of Rivers *et al.* (2013) that the choice of network construction technique is important and must be consciously based on the archaeological case it aims to represent, and it has presented a strategy through which such a decision can be made.

Additionally, this study has found that the application of LCPs instead of regular geodesic connections to construct networks has a significant impact on the resulting networks and the conclusions that can be drawn from them, for instance with the maximum distance network replacing the proximal point network as the most efficient one in terms of 'local' average path length (Table 8.1). This shows that incorporating the natural terrain, in this case through a LCP approach, can be important for better understanding how transport worked, or more generally, how space was utilised in the past.

	Temporal distances (derived from LCP)	Geodesic distances	Difference
Max. distance (90 min.)		85.4	
Max. distance (120 min.)	124.5	84.2	+44.0% ±12.4%
Proximal point (5 neighbours)	127.6	92.8	+36.9% ±13.9%
Proximal point (7 neighbours)	120.7	87.0	+37.5% ±6.2%
Delaunay triangulation	121.2	86.7	+39.0% ±6.4%
Gabriel graph	130.0	94.1	+37.6% ±7.3%
Minimum spanning tree	170.1	123.5	+36.6% ±5.4%
Efficiency (10% size increase)	143.5	107.6	+33.4% ±6.1%
Efficiency (25% size increase)	139.7	101.9	+38.1% ±7.1%
Efficiency (50% size increase)	134.0	97.1	+38.1% ±5.7%

Table 8.1. Average of the 'local' average path lengths (in minutes) to the forts from the nearest 25 settlements, shown in a comparison between temporal distances derived from LCPs and geodesic distances. LCPs are based on walking while carrying a load of 20 kg. Missing values are the result of forts not being reachable by at least 25 settlements (Groenhuijzen and Verhagen 2017; Section 6.5).

Using the LCP-based networks, archaeological questions can be addressed through formal network approaches. However, the various uncertainties involved in even reaching this step are often overlooked. These uncertainties for example may be the result of the chosen software (Gietl *et al.* 2008), the methods for calculating the costs of movement (Herzog 2013d), or the sources on which these costs are based (Herzog and Posluschny 2011) which have been treated to some extent in the given references. Since the current approach constructs networks on the basis of LCPs between settlements, the settlement dataset itself is another important source of uncertainty. In general, past studies in network analysis of transport in archaeology have paid little attention to the validation of results, even though network measures can become less stable when the data is imperfect (Borgatti *et al.* 2006) or when sampling the network dataset (Costenbader and Valente 2003). To address this potential problem, a robustness analysis was applied on local network metrics in the constructed network (Groenhuijzen and Verhagen 2016; section 6.3).

The robustness analysis was carried out in a model written in NetLogo (Wilensky 1999), a software package not commonly used for network analysis but useful through its easy accessibility and parallel processing capabilities. In the model, a single network was repeatedly constructed from scratch by iteratively adding sites to the network, and recalculating the local network measure of betweenness centrality. By tracking the development of this measure throughout the iterative construction of the network, a stabilisation point can be established, i.e. the point at which the measure has reached the value it retains until the network is fully constructed. If this happens well before the network is complete, the network measure on this site could thus be considered relatively robust.

The study found that 64% of all sites in the network have a betweenness centrality measure that is relatively robust. This rises to 81% when only considering sites that have a high betweenness centrality, which from an archaeological point of view are often considered to be important sites in the network as a high betweenness centrality indicates a high amount of control over the network. These results have implications for the application of network analysis on archaeological networks; while a majority of sites is relatively robust (i.e. not susceptible to slight changes in the site dataset) and thus is trustworthy enough to warrant an archaeological interpretation regarding roles in the network, this is not the case for a considerable amount of other sites.

8.3.4 Applications

After the construction of a network, the dataset of settlements and modelled transport connections becomes accessible to a more quantitative study in the form of network analysis. In this research, two studies have been carried out in the context of the Dutch *limes* area. Firstly, how were goods moved from the local population to the military population? Secondly, what is the role of stone-built rural settlements, a small subset of the rural settlement dataset, in transport networks? Since the Gabriel graph was found to be the best representation of a local transport network (Groenhuijzen and Verhagen 2017), this network structure was used to model local transport networks from the LCP dataset. The rural settlement dataset was filtered for chronological reliability using the methodology described by Verhagen *et al.* (2016b; section 3.4.2), resulting in a diachronic dataset of 636 sites (58% of the original size). Per time period, the number of rural settlements ranges between 284 (Late Iron Age) and 587 (Middle Roman Period B) (section 6.4.2).

Regarding the first question (section 6.4.3), two contrasting hypotheses were posed: one in which all goods flowed from each rural settlement directly to the nearest fort, and an alternative one in which goods were gathered at an intermediary site before moving in bulk to the fort (a dendritic hierarchic system cf. Willems 1986; Vos 2009). The premise of the latter hypothesis is that the most ideal gathering point is on average 'closer' to the rural settlements than the forts themselves. As potential intermediary sites, a selection was made of towns, *vici*, stone-built rural settlements, large rural settlements and settlements containing *horrea*. The hypotheses were tested using the network measure of path length, expressed in minutes of travel time over the links in the network (derived from the LCPs). For the alternative hypothesis to be valid, the sum of the path lengths (L) to reach the intermediary site (i) from a number of settlements (s) in addition to the path length of the intermediary site to the fort (f) should be lower than the sum of the path lengths to reach the fort directly (Eq. 8.2). Since provisioning is more likely to occur from the settlements that are near than ones that are further away, the total path length was calculated for the 25 nearest settlements.

$$TPL_{intermediary} < TPL_{fort}, \text{where:} \tag{8.2}$$

$$TPL_{fort} = \sum_{s} L(s, f)$$

$$TPL_{intermediary} = L(i, f) + \sum_{s} L(s, i)$$

The results (Fig. 8.5) shed light on how the provisioning of the Roman army may have worked. Fairly little can be said about the western part of the Dutch *limes* area (corresponding to Katwijk-Brittenburg until Utrecht), since very few sites have been identified as potential intermediary sites. The few ones that are, are so distant from the forts that they may have functioned as an intermediary site for more than one fort. In terms of total path length they are more efficient than the forts themselves as gathering sites, making the alternative hypothesis more likely. Additionally, it is possible that the forts themselves functioned as gathering places for their local area. In contrast, a large number of intermediary sites are available in the central part of the Dutch *limes* area (Vechten and Rijswijk). A number of these were found to have a lower total path length than the forts, although this is not true for all sites. Interestingly enough, almost all sites that have been identified as 'large' rural settlements (Vos 2009) have a lower total path length than the forts, whereas vici and some stone-built rural settlements do not. In the eastern part of the Dutch *limes* area (from Maurik to Herwen-De Bijland) almost all intermediary sites have a lower total path length than the forts, indicating that the alternative hypothesis is more likely in this area. The difference between the central and eastern parts may be caused by a more diffuse settlement pattern in the eastern part of the Dutch *limes* area; on average, settlements in the central part are closer to the forts than in the eastern part. This could have resulted in an increased need for intermediary sites in a provisioning system in the eastern part of the Dutch *limes* area.

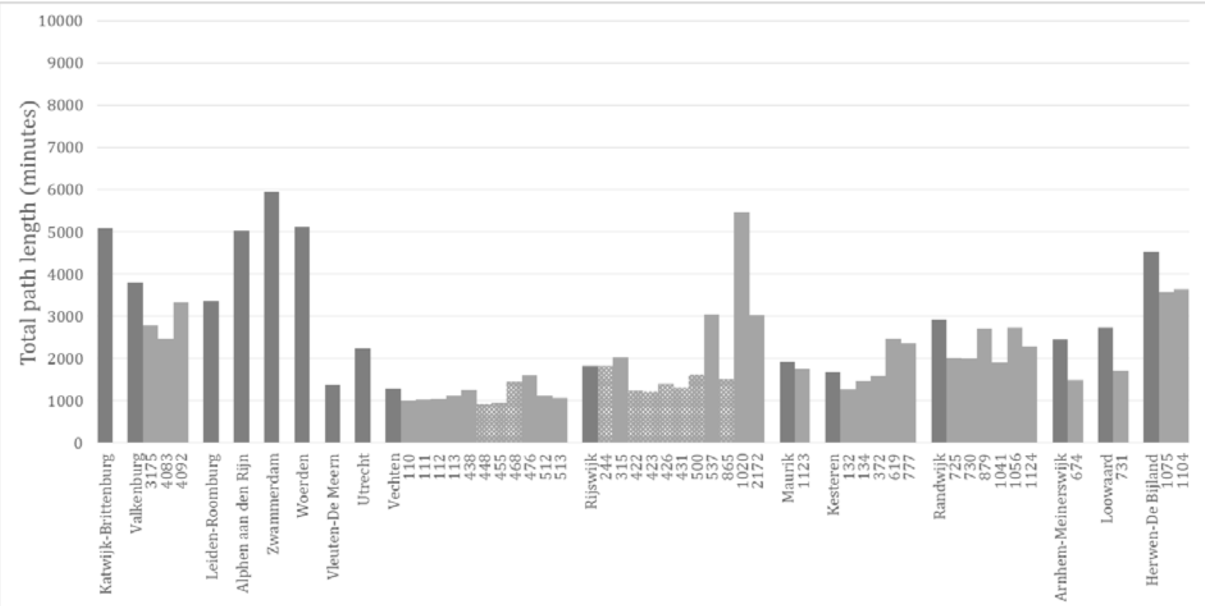


Figure 8.5. Comparison of the total path length to reach forts against total path length to reach forts via the selected intermediary sites (alternative hypothesis), measured from the 25 nearest settlements in the network for walking while carrying a load of 20 kg. The intermediary sites (light grey colours) are grouped by the nearest fort (dark grey colours), with 'large' rural settlements in the Kromme Rijn region shown through hatching. For locations see Fig. 8.1.

The second study revolved around the role of stone-built rural settlements in transport networks, more particular, if the position of these settlements in transport networks may have led them to grow in importance and become stone-built (section 6.4.4). This was approached using the network measure of betweenness centrality, which represents the amount of control a site has over movement in the network. More explicitly, the question is thus if at any point in time (but especially before becoming stone-built) there is a notable/significant difference in betweenness centrality for the stone-built rural settlements compared to other settlements?

For this analysis, the stone-built settlements were compared to their ten nearest neighbours, since betweenness centrality is also dependent on the location of sites in the network as a whole, and it is more interesting to compare stone-built settlements to their nearest neighbours to see if they hold some remarkable position in the network. If the betweenness centrality was more than one standard deviation away from the mean betweenness centrality of its ten nearest neighbours, it was deemed to have occupied such a notable position in the network (Table 8.2).

	LIA	ERP A	ERP B	MRP A	MRP B	LRP A	LRP B
n	18*	20*	21*	27	32	23	23
n with $C_B \geq \overline{C_{B\,10\,nn}} + \sigma_{10\,nn}$	7	5	8	8	8	5	3
% with $C_B \geq \overline{C_{B\,10\,nn}} + \sigma_{10\,nn}$	38.9	25	38.1	29.6	25	21.7	13.0

Table 8.2. Total number of stone-built rural settlements per time period (n), and the numbers and percentage that have a betweenness centrality (CB) that is more than one standard deviation above the mean betweenness centrality of the ten nearest settlements. LIA = Late Iron Age, ERP = Early Roman Period (A/B), MRP = Middle Roman Period (A/B), LRP = Late Roman Period (A/B). *Sites in the LIA-ERP B interval were regular post-built rural settlements, and only become stone-built in the MRP A (Section 6.6.4).

For the Late Iron Age-Middle Roman Period B interval, roughly a third of stone-built rural settlements exceed the mean betweenness centrality of the ten nearest settlements by more than one standard deviation. This is more than would be expected, since at any time only 5-7% of all rural settlements are (or would later become) stone-built. A total of 17 out of 33 stone-built rural settlements exceeded the mean by more than one standard deviation at any point in time, and only three did so in the Middle Roman Period at the latest. The other 14 settlements did so already in the Late Iron Age-Early Roman Period B interval. It can thus be interpreted that one of the reasons why these sites became stone-built in the Middle Roman Period is the potential for control that these sites have over movement in transport networks in the preceding time periods. This cannot be the only reason however, since there are 16 stone-built rural settlements that do not stand out from their neighbours, and likewise there are rural settlements that do stand out yet have never become stone-built.

Comparing the results of the second case study to the first one presented in this section, it was found that some stone-built rural settlements that do not stand out in terms of betweenness centrality, were able to potentially fulfil their role as intermediary site in provisioning systems. This shows that a settlement may have become stone-built for more than one reason related to centrality in local transport networks: because it can be easily reached by other settlements, or because it needs to be traversed to reach other settlements.

8.4 Settlement location analysis

8.4.1 Introduction

The location of settlements in the landscape has long been of interest to archaeologists, but many studies do not go much further than incorporating the natural terrain. Less frequently, other components are included, such as social, cultural or historical influences. This study has studied the location of settlements through a multivariate approach (Chapter 7), taking into account the natural palaeogeography, (distance to) rivers and streams, forts, transport networks (using the Gabriel graph constructed from the LCP dataset), potential intermediary sites in transport networks, and the influence of the historical landscape (previously existing settlements). The question that is studied can be put quite simply as: what governed the location settlements in the Dutch Rhine-Meuse delta? However, since the primary interest of this research lies on the relation between the military and the rural population, the question can also be specified as: can the location preferences of rural settlements shed light on the interaction between the local population and the military population?

8.4.2 Methodology

A binomial logistic regression was applied to investigate the relations between and the individual importance of the aforementioned variables for rural settlement location in the Dutch *limes* area. The dependent variable of the regression model is binary: a rural settlement is either present or absent. For this reason, 10,000 non-site locations were modelled to include in the dataset alongside the settlement locations. The rural settlement dataset itself was filtered for chronological reliability following the methodology outlined by Verhagen *et al.* (2016b; section 3.4.2) and for spatial uncertainty (section 7.2.2). This resulted in a diachronic dataset of 450 sites (41% of the original size), mostly focussed on the central and eastern river area.

Most parameters are relatively straightforward to implement, the exceptions being the natural palaeogeography and the historical landscape. A settlement location in the natural landscape is not just decided by the point location, but also by what kind of landscape elements are available in its vicinity. To solve this, the natural palaeogeographic composition of each site's vicinity was calculated within a 500 m range, and cluster analysis was applied to create 'landscape types' (Verhagen *et al.* 2016b). For the historical landscape, 'heritage maps' were created using an incremental kernel density approach following the methodology of Nuninger *et al.* (2016).

The logistic regression was applied with a Monte Carlo method approach for each time period, where in each of the simulation runs, half of the rural settlements during that time period were randomly selected as training dataset to fit the regression model, along with a set of non-sites of equal size. The other half of the rural settlements served as part of the testing dataset, again with an equal-sized set of non-sites. The testing dataset was used to assess the predictive capability of the model.

8.4.3 Results

The logistic regression found that the historical landscape and distance to the transport networks were important factors for settlement location (Section 7.4). The former indicates that sites are more likely to appear in areas where other sites are already present. Of course the distance to transport networks goes hand in hand with the historical landscape; the transport networks are modelled on the basis of the settlements, and thus tend to have a higher density in areas where site density is also higher, and thus the heritage factor is stronger. Furthermore, both the settlements and the transport network tend to concentrate on the levees. These variables thus strongly interact with each other and with the natural landscape (specifically the 'levees' category), which is evident also in this analysis. The other considered factors, namely the distance to rivers and streams, forts, and intermediary sites in transport networks, are not found to be important for the location of rural settlements in the Dutch *limes* area. An interpretation that can be attached to this is that the location of rural settlements is governed by landscape suitability and the potential to interact with other rural settlements, but not particularly to interact with the military population or with sites that may have accommodated interaction with the military population.

Furthermore, some interesting shifts were found in settlement location preferences through time. During two intervals within the Early Roman Period and Middle Roman Period there was a shift towards more 'marginal' areas, both in terms of the natural environment as well as the settlement landscape. This may be explained as a result of changing modes of production or as a result of increasing pressure in the core habitation area on the levees. The opposite trend is seen in the Late Roman Period, where new settlements tend to appear within the core habitation area rather than along the margins, perhaps because the lower population density did not necessitate such a move (section 7.5).

8.5 Conclusion

The LCP modelling, network studies and settlement location analysis presented above have provided some new and valuable insights into the properties of movement on the local scale in the Dutch Rhine-Meuse delta, the potential functioning of the Roman military provisioning system, the role of individual sites within these local transport networks, and the relation between settlements and their natural and social environment. For example, the case studies applied on the modelled transport networks have found that at least for the eastern and central parts of the study area it is more likely that transport from the local to the military population was carried out through intermediary sites rather than through the forts, supporting the archaeological hypothesis of a dendritic hierarchic settlement system. Furthermore, the role that individual settlements have in these networks of transport could have given rise to the higher-status stone-built settlements, as some of these have been shown to be valuable as potential intermediary sites and/or to be centrally located on routes between other settlements. The settlement location analysis has found that settlements tend to concentrate on the levees in areas where settlements already existed previously and close proximity to transport networks. Other factor were less important, showing that the location of new settlements is mostly governed by landscape suitability and the potential to interact with other rural settlements, and not particularly to interact with the military population. The findings stated above are valuable for archaeologists to further their thought on interactions between the local and military population of the Dutch *limes* area.

Of similar importance are the methods through which these results are achieved. By formulating the archaeological questions in such a way that they can be addressed by the computational approaches, these studies can provide new insights that were not readily extractable from the archaeological data beforehand. In contrast to tailoring an archaeological problem to the computational approach, which is sometimes offered as a criticism in some computational studies (e.g. Brughmans 2013b; Herzog 2014a), formulating a question- or hypothesis-based approach and tailoring the computational approaches to that topic can add value to the application of computational approaches in archaeology.

More specifically tailored to the approaches applied in this research, the application of LCP analysis to model local transport connections has proven valuable, as it allows for the inclusion of the natural terrain, and this was found to have significant impacts on following analyses. The application of network analysis on problems that are specifically suitable to be addressed as networks (such as questions on the Roman provisioning system) has proven to be valuable and lead to interesting archaeological conclusions, and the results of this research thus encourages similar future problems around transport to be addressed as networks as well. For example, the same datasets and methodologies can be used to study the top-down distribution of goods from the Roman military to the local population, such as the distribution of imported pottery. The methodologies developed here can also be applied on different datasets as they are not spatially or chronologically limited to the Dutch part of the Roman *limes*; examples could be the Late Iron Age land- and water-based distribution of La Tène glass artefacts in continental Europe (Roymans *et al.* 2014) or the Medieval trade connections that formed the trackways that are still visible today in the heathlands in Drenthe (northern Netherlands).

Important in the application of computational approaches is the need to account for uncertainty in the data and methods, and for the validation of the results. Wherever possible, in this research it was attempted to take uncertainty into account, such as the spatial uncertainty of the natural palaeogeographic reconstruction (section 2.5) and the chronological uncertainty in the site dataset (Verhagen *et al.* 2016b; section 3.4.2). The results of the network analysis were subjected to a robustness analysis (Groenhuijzen and Verhagen 2016; section 6.3), in order to make the interpretations drawn from these results more reliable. However, there is still more work to do in this area. Archaeological data is inherently uncertain and incomplete, and quantitative approaches thus remain susceptible to such data problems; this research only shows some ways in which these uncertainties can be incorporated into the research to strengthen the output.

9 Conclusion

This dissertation focussed on the palaeogeographic aspects of the 'Finding the limits of the *limes*' project, consisting of a reconstruction of the natural palaeogeography and a reconstruction and analysis of the cultural landscape, specifically regarding local transport networks and settlement patterns. A detailed overview of the results of this research were presented as a synthesis in the previous chapter. This chapter focusses on some main concluding ideas, and furthermore, aims to identify the prospects for future research.

An important part of this project was the construction of datasets that are suitable to be used for further (spatial) computational analysis. Firstly, this consisted of the palaeogeographic map, which at the start of the project was not yet available for the entirety of the research area. This study followed the methodology of Van Dinter (2013), which involves the manual combination of various source datasets, to extend the palaeogeographic reconstruction of the Old Rhine region to cover the western and central parts of the research area (Chapter 2). A more automated approach was used to reconstruct the natural palaeogeography of the eastern parts of the region. Simultaneously with this project, another detailed palaeogeographic reconstruction for the Rhine-Meuse delta in the Roman Period was developed by Pierik (2017) using a more procedural approach. Despite the differences in methodology, the results are fairly similar and allow for many of the same analyses to be applied (e.g. De Kleijn 2018, 125–202). Future research may benefit by a better integration of both approaches, with the more automated procedures using large datasets of boreholes and ^{14}C-dates developed by Pierik *et al.* (2016; 2017) and a focus on local (archaeological) source data following the methodology of Van Dinter (2013). This may potentially lead to new interpretations that are difficult to achieve only on the basis of the available borehole data due to fluvial erosion processes, such as the hypothesised connection between the Meuse and Waal near Kessel in the Late Iron Age (Roymans 2017).

The second vital base dataset that was required for the analyses performed in this study concerns the archaeological sites. The results of archaeological research in the Netherlands, ranging from excavated sites to isolated finds, are registered in the national archaeological database Archis.[1] However, this data is very heterogeneous and difficult to directly subject to detailed quantitative analysis. Philip Verhagen worked on the construction of the site dataset following a standardised methodology based on one developed by Vossen (unpublished, briefly described in Vossen 2007, 40), consisting of the definition used to translate a set of observations (find spots) to a site, the interpretation of sites and the establishment of a site chronology (Verhagen *et al.* 2016b; Chapter 3). The new archaeological site dataset is more reliable in terms of consistency of information, allowing for more detailed quantitative analysis, as was shown for example in its applications in the study of local transport networks and site location in this thesis (Chapter 4-7).

Important components of both the natural palaeogeographic map and the archaeological site dataset are the inclusions of explicit uncertainty. Uncertainty is a common feature in many archaeological datasets (Cooper and Green 2015), both in terms of completeness of the data and quality of the information, yet the attention paid to those uncertainties is usually limited (Verhagen *et al.* 2016b, 309). In this project, it was aimed to make uncertainty and explicit part of the analysis. For the natural palaeogeographic dataset, this meant the explicit mapping of uncertain areas, an uncommon feature in palaeogeographic research (section 2.5). The spatial uncertainty was used as in a case study to show its effects on least-cost path modelling (section

[1] archis.cultureelerfgoed.nl

5.3.3), and it was used to filter the archaeological site dataset for spatial reliability in the site location analysis (Chapter 7). For the site dataset, a method was developed to reinterpret the chronological information (Verhagen *et al.* 2016b; section 3.4.2). This allowed for the filtering of the dataset for chronological reliability, which in this study was used in the analysis of local transport networks (Chapter 6) and the site location analysis (Chapter 7). In these analytical approaches the explicit inclusion of uncertainty was found to allow for more reliable and robust results. Future research can benefit from developing such methods further, for example, by performing analyses on a dataset with various thresholds of reliability so that the resulting variance of the output and in turn the robustness of the interpretation can be better assessed.

Concerning the study of the cultural landscape of the Dutch part of the Roman *limes* and particularly the spatial and economic interactions between the local and the military population, one of the main focal points of this study were local transport networks. Prior to the analysis of networks in Chapter 6, the focus was on reconstructing potential local transport routes in Chapter 5. Multiple modes of transport were modelled, including walking while carrying various loads and mule- and ox-cart transport, as well as water-based transport using dugouts as part of multimodal networks. The first results for the Kromme Rijn region showed that most of the transport movements on the local scale would have occurred over the central levees where settlement density is highest. The *castella* and the military road along the Rhine are more peripheral in comparison to these local transport movements; the military road had little function for local scale transport and would probably be more efficient just for movement between the forts (Groenhuijzen and Verhagen 2015; section 5.3.1). An opportunity for future research would be to study these different scale levels of transport in conjunction. For example, what would be the quantity of flow over the various transport connections, considering both a surplus production by the local population and imports to provision the Roman army in the forts (cf. Kooistra *et al.* 2014)? Other aspects that are understudied so far and thus remain an opportunity for future research is the role (political) institutions in governing transport decisions, as well as the impact of seasonality on land-based transport, the latter of which is included for instance in the ORBIS model (Scheidel 2014) but is thus far is not yet incorporated in more detailed studies of Roman transport systems. Finally, the recent finds of local infrastructure (e.g. Roymans 2007; Roymans and Sprengers 2012) as well as the potential role of fords over rivers and streams could be incorporated into least-cost path modelling to achieve more archaeologically 'accurate' results.

In the analysis of the least-cost path results, one of the findings was that water-based transport was likely less important on the local scale (section 5.3.2). An explanation for this is that the majority of movement between the rural settlements and the forts would be generally south-north directed, whereas most rivers and streams have a general east-west direction. While water-based transport can be an important component of the socio-economic structure in the Roman empire (e.g. Franconi 2017), many aspects remain unknown, such as the availability of water-based transport modes to the local population (such as dugouts) or the presence of harbours or landing places. Furthermore, movement over rivers and streams is highly dependent on seasonality, with hindering factors including flooding, drought and freezing of the river. The influence of water-based transport in the Dutch *limes* area or in the northwest-European parts of the Roman Empire in general thus remains an area that can be looked into further in future research.

An understudied part of least-cost path modelling in general is the sensitivity and validation of pathway models. Sensitivity analysis can be applied on the cost definition, cost surface creation and least-cost path calculation, yet current archaeological studies mostly limit themselves to a validation of the output through a comparison with empirical data (Verhagen *et al.* 2018). Least-cost path modelling in future research may benefit from a better integration with sensitivity analysis. This would be best served through the development of new software approaches that can accommodate this, as GIS is not the best tool for statistical analysis. In addition, the development of a toolbox unrelated to a specific GIS would provide the opportunity to move away from the current rigid 'black-box' approaches in least-cost path modelling, which are often limited to the possibilities of each specific GIS package, and would allow future research to make more conscious and transparent choices in path modelling to ultimately generate more robust results. Examples of additions to such a toolbox would be the optional movement over a raster in more than eight directions (i.e 'knight's moves' or more complex moves; Herzog 2014; Groenhuijzen 2018a), the inclusion of different path finding algorithms (e.g. Dijkstra and A* algorithms; Dijkstra 1959; Hart *et al.* 1968) and different cost functions (e.g. Tobler 1993; Minetti *et al.* 2002). Furthermore, it would be valuable to better integrate path modelling, network approaches and path detection (e.g. remote sensing) approaches to improve the understanding of territorial dynamics and human-environment interactions through movement (Nuninger *et al.* 2018).

Chapter 6 dealt with the study of the local transport networks of the Dutch part of the Roman *limes*. Before the analysis of questions of local transport in section 6.4, some important methodological issues were discussed first. Firstly, consideration was given to the method of network construction that would produce the best representation of a local transport network in the Dutch *limes* area. Currently there is no standard best practice for the construction of a network on the basis of least-cost paths (Groenhuijzen and Verhagen 2017). However, through the evaluation of which technique produces the most efficient network for the movement between the rural settlements and the forts, the Gabriel graph was chosen as the structure to be used for further analyses in this study (Groenhuijzen and Verhagen 2017; section 6.2). Such a conscious approach to the choice of network construction technique is advised for future studies involving least-cost path and network analysis. Alternatively, future studies in the Dutch *limes* area or other study regions may adopt gravity models (e.g. Evans and Rivers 2017) and/or adopt models of production and consumption to construct networks of local transport. Such an approach could provide a comparison with the current study, not just methodological but also in terms of questions of local transport and distribution of goods from the rural to the military population, which may lead to more robust analyses and interpretations regarding the networks of local transport in the Dutch *limes* area.

A second important methodological aspect is the recognition of uncertainty in applying network approaches to the constructed networks of local transport. The network analysis results may be influenced by the absence or false presence of sites in the network. In order to study the robustness of the analysis results, a model was developed that iteratively builds networks from the existing datasets so that the dependency of network measures on the completeness of the network structure could be evaluated. It was found that a majority of network analysis results are robust, but that it must be kept in mind that there are some results which are less reliable (Groenhuijzen and Verhagen 2016; section 6.3). The explicit recognition of uncertainty would be valuable addition in future network studies, and could be expanded by including uncertainty in the network links (e.g. through changing the value of links that are weighted on the basis of travel time, owing to the least-cost path approach).

Section 6.4 presented two case studies using network analysis approaches to address archaeological questions related to local transport. The first question concentrated on the distribution of goods from the rural population to the military population. This was tested by positing two contrasting hypotheses that are explicitly testable through the network measure of path length. It was found that a method of distribution through intermediary sites in most cases by more efficient than the movement of goods directly from rural settlements to the forts, although a dual system where both methods of distribution have co-existed may have been possible for some forts. The second case study of section 6.4 studied the role of stone-built rural settlements and their role in local transport networks. It was found that a number of stone-built settlements had a higher betweenness centrality than the average settlement in their vicinity, and the number of stone-built settlements with this property was greater than would be expected based on the ratio between stone-built and post-built settlements. This could indicate that these settlements became stone-built (partly) through having control over transport movements in the network. While these results already provide interesting insights into the functioning of local transport in the Dutch *limes* area, there are still questions that are left unanswered and remain open for future archaeological research. For example, why were some stone-built rural settlements found to be relatively important in local transport networks, functioning well as an intermediary site in distribution networks or having control over movement between other settlements, while other stone-built settlements are not? Vice versa, why are some 'ordinary' post-built settlements found to be important in local transport networks in terms of network measures such as betweenness centrality, yet did not grow out to become large and/or stone-built rural settlements?

These studies are a good showcase of how an archaeological idea can be tested and thus given more weight by expressing the problem in explicit hypotheses that can be evaluated using concepts of network science. With these network approaches, both the functioning of transport networks as a whole and the role of individual settlements in these networks can be studied in detail. It can thus be stated that future studies that utilise network approaches should avoid the pitfall of uncritically adopting the most popular network techniques that are sometimes found to be a poor fit to the archaeological problem, and instead should take a question-driven approach, where first the archaeological problem is identified, and secondly the most appropriate method to address that problem is selected (Brughmans 2013b, 654).

Chapter 7 presented a site location analysis, specifically focussing on the study of location preferences for rural settlements. Through the individual analysis of variables that potentially influence site location and a multivariate approach, it was found that the most important factors for settlement location are the historical landscape and distance to transport network. Furthermore, the results showed a shift in settlement location preferences through time, moving towards the more 'marginal' areas (both in terms of the natural and the cultural landscape) in the Early and Middle Roman Periods and in the opposite direction in the Late Roman Period, perhaps as a result of changing modes of production or increasing pressure in the core habitation area on the levees in the Rhine-Meuse delta. The results of this analysis prove that the inclusion of cultural/social factors have a valuable impact on understanding settlement patterns through site location analysis. Future studies in site location analysis should thus not underestimate these factors. It could be improved further by an even stronger integration of aspects such as transport networks, such as a potential for playing a role as an intermediary site (as opposed to the distance to preselected intermediary sites that was included in this study).

In the introduction of this thesis it was stated that one of the most challenging tasks for an archaeologist is imagining the past. This palaeogeographic analysis of the Dutch part of the Roman *limes* aimed to shed more light on the cultural landscape and the spatial and economic interactions of the local and the military population in the region. Through a variety of spatial and network analytical approaches, more insight was gained in the properties of local transport routes in the Dutch *limes* area, the functioning of transport networks that facilitated interaction between the local and military populations, and the factors that structured the settlement landscape. Furthermore, this study has developed or adopted innovative computational archaeological approaches, including understudied aspects such as the explicit inclusion of uncertainty in both the archaeological dataset and the methods used, and has shown how such approaches can be used to address current archaeological questions in Dutch *limes* research.

10 References

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Summary in English

Chapter 1: Introduction

The primary aim of this study as part of the larger 'Finding the limits of the *limes*' project is to analyse and reconstruct the cultural landscape of the Dutch *limes* area, more specifically looking at the site and settlement patterns, the transport networks and their interrelationship with the natural environment.

Firstly, in order to understand spatial developments and patterns in the cultural landscape in relation to the natural landscape, the natural landscape must be accurately known first. Since the current project focusses on both the Cananefatian as well as the Batavian *civitates*, the first main aim is to extend the existing reconstructions of the natural landscape to cover the entire Dutch *limes* area. From a more methodological standpoint however, a concern is that there are implicit and sometimes explicit uncertainties in every palaeogeographic reconstruction. A secondary aim is therefore to make these uncertainties clear and definable, and possibly test the influence of the uncertainty on further analysis.

A second main aim of this thesis is a reconstruction and analysis of transport networks that were active in the region. Elaborating on that, the first aim here is to quantify and make explicit the factors that govern transportation, in terms of agents, frequency, goals and modes of transport, as well as the role of the natural environment promoting or hindering transport. The results can be used for transport network reconstruction. The application of network analysis on such modelled transport networks potentially allows us to infer information about archaeological questions such as the hierarchy in settlements and the role of certain individual sites (both settlements and Roman military sites) in the network, which can be tested against archaeological evidence.

The third main aim of this thesis involves an analysis of individual sites within the landscape. Knowing the landscape position of a site can inform us about the potential governing factors of site location decisions. To achieve this, sites are firstly analysed looking at individual factors and secondly through a multivariate analytical approach, looking at all possible governing factors simultaneously, from which information can be inferred on the relative importance of individual factors, the relationship between individual factors or the amount of variation in the site distribution that is explained by the factors under consideration.

Chapter 2: Natural palaeogeography

This chapter presents the work done on the natural palaeogeography of the Dutch part of the Roman *limes* within the 'Finding the limits of the *limes*' research project. At the start of the project, a reconstruction of the natural palaeogeography of the Dutch *limes* area, suitable for detailed quantitative analyses, was not yet available. The only palaeogeographic reconstructions available for the entire research area are too coarse for such approaches. Projects with detailed palaeogeographic reconstructions have been undertaken in the past for smaller areas, examples being the project on the western Netherlands in the first millennium and the project on the Roman *limes* in the Old Rhine area. The work done in the latter project has been incorporated in this study, and the methodology for reconstruction has been applied to extend the map to cover the entire research area.

Furthermore, even though detailed palaeogeographic reconstructions were available for some regions of the Dutch *limes* area, the full analytical potential of such reconstructions is yet to be explored. The palaeogeographic map of the Dutch *limes* area during the Roman Period is constructed with the intention of using it for spatial analysis, including path modelling, network construction, site location analysis and agricultural production models.

An addition that was added to this work that was underappreciated so far in palaeogeographic research is the explicit acknowledgement of uncertainty. In the palaeogeographic reconstruction of the Dutch *limes* area in this project, it is aimed to make uncertainty more explicit by building uncertainty maps and including the various sources of uncertainty. When considering the use of palaeogeographic maps for spatial analyses and modelling it is important to know where uncertainty resides, as they can influence the outcome of the research.

Chapter 3: The archaeological site dataset

One of the most vital components for a regional study is a reliable archaeological site dataset upon which the analyses and interpretations can be based. This chapter presents the archaeological site database used in this study.

Most archaeological information in the Netherlands is registered in the national archaeological database ARCHIS, where it is stored at the level of individual observations (essentially equivalent to findspots). To arrive at an archaeological site, an interpretation thus has to be made of the observation data. One observation or multiple observations together form one site in this study according to predefined criteria. The first of these criteria is the number of finds in observations that are within a defined spatial range, set here at 10. The second criterion for defining a site is that spatial range in which observations are made, set here at a radius of 250 m. After defining an observation or a number of observations as an archaeological site, the next step is to assign an interpretation regarding the nature of that site. In general, the site classification in this project follows the structure established in the preceding studies of the Dutch part of the Roman *limes*. Settlements are subdivided between military settlements (further subdivided into *castra*, military camps, *castella*, watchtowers and undefined military settlements) and non-military settlements (further subdivided into larger civil settlements, stone-built rural settlements and regular rural settlements).

Although some sites (for example the excavated Roman military ones) can be dated quite precisely, the majority of sites in the database have only limited information available on which the chronology can be established. Rather than using exact time spans, the sites were dated according to the archaeological time periods used in the ARCHIS database. However, with this methodology the dating quality and precision can vary greatly over the dataset, potentially affecting any further analyses. The chronological information associated with the observations in the ARCHIS database is therefore used to reinterpret the dating of archaeological sites. For this, a Monte Carlo-simulation approach is applied wherein the number of finds in a period is calculated per run based on probabilities of existence. Based on the principle that a site is assumed to have existed when at least 10 finds were present on that location, the probability of site existence can then be given per time period on the basis of the number of runs with 10 or more co-existing finds. These values can be used in further (spatial) analyses, as a site dataset can be constructed that is based on probabilities of presence during a certain time period, rather than the original chronological information of varying quality and precision.

Chapter 4: Characterising transport systems in the Dutch part of the Roman *limes*

One of the aims of this study is to reconstruct and analyse transport networks that were active in the region, in the first place by identifying and quantifying the factors that govern movement in general as well as the movement of goods in particular. This chapter deals with the characterisation of transport, particularly for the Dutch part of the Roman *limes*.

Transport is the subset of movement or mobility where people, animals, goods or information are transported from one location to the other. Firstly, an important distinction has to be made based on the aspect of the scale of transport movements. Three interconnected networks can be recognised: an imperial exchange network, interprovincial exchange networks and regionally centred, provincial exchange networks. The latter can be further subdivided into interregional networks, regional networks and local networks. The primary interest of this study is on transport within the research area, and particularly concerning transport between the local and the military population. The first level here pertains interregional transport, meaning the movement of goods or people over larger distances (across *civitas* borders), but still within the region contained by the research area, namely the Batavian and Cananefatian *civitates*. The second level concerns regional transport, i.e. transport within a *civitas*. The lowest scale level of transport concerns the transport over relatively short distances, i.e. local scale transport. An example is the transport of goods from settlements to local markets, the majority of which likely concerned agricultural surplus production.

The purpose of transport can vary. Ones that can immediately be thought of are transport through economic market forces, social interaction, political representation or military action. Economic transport, which generally concerns the transport of commodities between production, market and consumption sites, may be the most frequently studied and most quantifiable aspect of transport. A large part of transport movements occurring in the research area must have been at least partly of an economic nature. The Roman occupation of the Dutch river area placed new demands on the local rural population, such as taxation, which could have been in the form of surplus production (or manpower for the Roman army in the Early Roman Period) or in the form of money that was raised by selling produce at local markets. The newly arising economy with unprecedented supply and demand structures must have greatly increased the number and scale of transport movements, particularly those of staple foods from production sites to markets and consumption sites.

The military population and the local population of the Rhine-Meuse delta had a multitude of transport modes available to them, each with their own specific characteristics. By no means are these modes of transport are always competitive: they may and most likely will have functioned as part of a complementary system. In this chapter a review is provided of the available literature data on the characteristics of various modes of transportation. Concerning land-based transport, in particular local transport in the Dutch *limes* area, the most common method of transport would have been foot-based travel. Animal-based transport is also available in the Dutch part of the Roman *limes*. This will primarily have involved oxen, as horses seem to not have been used as pack and certainly not as draught animals often, and mules must be imported from outside the region. Four different watercrafts are treated in the review of water-based transport, namely prams, punters, galleys and dugouts. Galleys will have had a primary function as a military craft and not much is known about punters since only one has been found in the Dutch river area. Prams are the most iconic type of water-based transport in the Dutch part of the Roman *limes*, used for the bulk transport of heavy construction materials and less heavy goods such as merchandise. In contrast, dugouts can be seen as the representative of water-based transport on more local scales.

They are the continuation of local traditions of sailing and were continuously in use even during the presence of the larger prams.

With the information presented in this chapter it has become clear that the level of understanding of transport in the Roman Period is quite good in terms of transport that is happening at supraregional scales, due to the availability of both archaeological information and written sources, as well as a long tradition of research. However, much less is known about transport on the local and regional scales, such as the interaction between the local population and the military population in the Dutch part of the Roman *limes*. For a large part this is due to the fact that transport on the these scales is not mentioned in the written sources and leaves very few archaeological traces.

Chapter 5: Modelling transport connections

Since the interest of the current study is mainly in transport on the local scale in the Dutch part of the Roman Lower Rhine *limes* (as part of the complex of scales on which transport would have occurred), we have only very few archaeological remains to work with due to the immaterial nature of local transport movements. The lack of evidence for such a common activity as movement through a landscape is not a new problem in archaeology, and computational approaches have been used for some time to study movement and patterns of movement instead. The focus of this chapter is therefore on the various aspects of modelling transport in the Dutch part of the Roman *limes* through least-cost path (LCP) analysis.

The most important decision that has to be made when modelling LCPs for walking is the establishment of the costs that will be taken into account during the analysis. Out of the many functions available to calculate costs of movement, the equation offered by Pandolf *et al.* (1977) was used as it can readily incorporate terrain coefficients and carried loads. In contrast to the widespread availability of physiological and/or experimental functions for modelling the costs of walking, much less research has been done on modelling time or energy expenditure of animal-based transport modes. Instead, a combination of formulas is used that calculate traction force over various terrains. Besides land-based transport modes, the local and military population of the Dutch part of the Roman Lower Rhine *limes* have also used water-based transport options. In this study, water-based movement with dugouts is modelled as part of multimodal paths. In general, the calculation of a LCP of a multimodal transport connection follows the same methodology as that of unimodal land-based transport connections. The only difference that is made is in the costs of movement over rivers and streams, which now accommodate water-based movement rather than form a barrier for movement.

The modelling of transport connections presented in this chapter is successful in terms of understanding the interaction between movement and the natural environment, and the realisation of that interaction in the construction of LCPs. The results show marked differences between the modelled routes of foot travel and animal-drawn carts in terms of where people move using these modes, and a further variation is introduced with the use of dugouts. However, the modelling of LCPs of foot travel could be performed with more reliability based on a stronger tradition in physiological (and archaeological) research on movement on foot, whereas animal-based and water-based transport modes had to rely on fewer and less compatible sources to the situation of the Dutch river area.

Within categories of foot travel or cart-based transport there are further differences in terms of travel time. This is important when thinking about networks of transport, where time plays a role in deciding which of the modelled transport connections are part of the network and which are not. However, despite being able to make preliminary assertions based on the modelled routes such as that the Roman military road (the primary infrastructural feature that we know of) plays no role in local-scale transport connections due to its peripheral location in this case study of the Kromme Rijn region, potential transport connections modelled through LCPs do not readily tell us anything about the functioning of transport in the Roman Period when it concerns questions such as the movement of surplus production from the rural settlements and the provisioning of the Roman military population. This requires a further interpretation and analysis, which can be performed in the context of networks of transport.

Chapter 6: Transport networks in the Dutch part of the Roman *limes*

The goal of this chapter is to study local transport networks of the Dutch part of the Roman *limes* with concepts of network science. In each section one or more problems are identified, which includes both methodological and archaeological questions, and an approach was sought to address these problems.

Firstly, a comparison is made between various network construction techniques in section 6.2, to find the network structure that is closest to the archaeological reality it aims to represent. This is a necessary step that has to be undertaken in order to move from the dataset of potential transport connections modelled through a least-cost path approach to a network that can be analysed with concepts from network science. By setting some evaluation criteria that are archaeologically relevant, such as how easy it is to move goods from rural settlements to the *castella*, measurable through the average path length, a quantitative evaluation can be made of various network construction techniques. In this case the Gabriel graph is found to be the best network structure representation of a local transport network for the distribution of goods from the local to the military population, but similarly important, this section demonstrates an approach in which such a methodological problem can be suitably addressed with the archaeological reality in mind.

The application of network analysis techniques on archaeological networks also give rise to questions of uncertainty: how dependent are the results for instance on the completeness of the dataset? In section 6.3 the effects of uncertainty on network analysis results is investigated, by constructing a model that iteratively builds networks from the existing datasets so that the dependency of network measures on the completeness of the network structure could be evaluated. It is found that 64% of the sites have a robust measurement, meaning that the results are not dependent on that specific network structure but remain the same when for instance sites are missing from or are falsely present in the dataset. On the other hand, 36% is thus not that reliable, and this must be kept in mind when applying network analysis on archaeological datasets. An important aspect of this study is that it presented a methodology through which such a question of uncertainty with the archaeological datasets in mind can be addressed.

Section 6.4 focusses on the application of network analysis on the modelled transport networks. The first case study tests an archaeological hypothesis that posits that the (re)distribution of goods in the Dutch part of the Roman *limes* was achieved through a hierarchic dendritic system, where intermediary sites functioned in between the military population in the *castella* and the local population in the rural settlements. This hypothesis is tested by contrasting two hypotheses: a null hypothesis in which all surplus produced goods flow directly to the *castella*, and the alternative hypothesis in which goods were gathered first at predetermined intermediary sites before moving to the *castella* in bulk. The network measure of path length (which equates travel time in our study) is used to evaluate these hypotheses, and it was found that in most cases distribution through the intermediary site is more efficient than a direct distribution, making the alternative hypothesis that was posited by previous archaeological studies more likely than our null hypothesis, although there is also room for a dual system in which both methods of distribution of goods co-existed. This study is a good showcase of how an archaeological idea can be tested and thus given more weight by expressing the problem in more explicit hypotheses that can be evaluated using concepts of network science.

The second case study in section 6.4 studies the role of stone-built rural settlements in a bit more depth. More particularly, the question is asked if these stone-built rural settlements had a potential control over transport movements in the network that may have led them to becoming more important over time, a property that can be evaluated using the network measure of betweenness centrality. It is found that a number of stone-built rural settlements have a higher betweenness centrality than the average settlement in their neighbourhood, and this number is greater than would be expected on the basis of the ratio of rural settlements that are stone-built. Interestingly, in most instances this is already the case in the Late Iron Age or Early Roman Period, i.e. the pre-stone-built phase of these settlements. This could thus indicate that part of the reason that these sites have become important and ultimately have become stone-built is that they have a potential to control transport movements over the network. This study is a good showcase of how network measures can be used to study the role that individual settlements have played in transport networks.

In section 6.7 the reinterpreted chronological information following the methodology presented in Chapter 3 is used explicitly to test continuity and change in transport networks through time. It is found that the application of this new chronological information does not significantly change the resulting network structures compared to the original chronology, which is an important conclusion because otherwise the results of any analyses would only be dependent on the chronological methodology applied. Instead, the reinterpreted chronology is used to study changes with more chronological reliability. This study reveals that there is a high degree of continuity in local transport networks, and this continuity is higher than would maybe be expected on the basis of continuity in the settlement dataset, indicating that local transport networks are more persistent than the settlement pattern itself. Some variations are also noticeable in the level of continuity, which can be related to known periods of instability such as the Batavian revolt and the 3rd century border collapse.

Chapter 7: Site location analysis

In this research the interest in site location has several reasons: to determine the (natural, cultural/social or historical) governing factors of settlement location choices, to investigate settlement pattern development through time, and to serve as input data for models of agricultural production. The analyses presented in this chapter consist firstly of an analysis of the individual factors (including the natural palaeogeography, rivers and streams, forts, transport networks, potential intermediary sites in transport networks, and the influence of the historical landscape), and secondly a multivariate approach in order to study the relative importance of factors and how that possibly changes through time. The latter analysis uses a Monte Carlo method approach to develop a logistic regression model for the prediction of site presence and absence in each time period.

It is found that the historical landscape and the distance to the transport network were important factors for settlement location, showing that the inclusion of cultural/social factors such as the historical landscape as well as modelled transport networks has a valuable impact on such a settlement location study. In terms of results, some interesting shifts are found in settlement location preferences through time, with a shift towards more 'marginal' areas in the ERP A-ERP B and MRP A-MRP B intervals, in terms of both the natural environment as well as the settlement landscape. This may for example be explained as the result of changing modes of production or as a result of increasing pressure in the core habitation area on the levees. The opposite is seen in the LRP A-LRP B shift, where new settlements were primarily located within the core habitation area rather than along the margins, perhaps because the relatively low population density did not necessitate such a move.

Chapter 8: Synthesis / Chapter 9: Conclusion

These chapters present the general results of this part of the 'Finding the limits of the *limes*' project, and place it in the wider research context. They aim to summarise and showcase some of the innovative aspects of the study, either from technical, methodological or interpretative viewpoints. To do this, Chapter 8 utilises some case studies presented in this study in the realm of transport networks and settlement location in the Dutch part of the Roman *limes*. Formulated in a more general question, the goal of Chapter 8 is as follows: what has this spatial analytical study of the cultural landscape of the Dutch *limes* area contributed to the research field of computational archaeology and related fields, and what has it contributed to the archaeological understanding of the Dutch part of the Roman *limes*?

The LCP modelling, network studies and settlement location analysis presented in this study have provided some new and valuable insights into the properties of movement on the local scale in the Dutch Rhine-Meuse delta, the potential functioning of the Roman military provisioning system, the role of individual sites within these local transport networks, and the relation between settlements and their natural and social environment. For example, the case studies applied on the modelled transport networks fin that at least for the eastern and central parts of the study area it is more likely that transport from the local to the military population was carried out through intermediary sites rather than through the forts, supporting the archaeological hypothesis of a dendritic hierarchic settlement system. Furthermore, the role that individual settlements have in these networks of transport could have given rise to the higher-status stone-built settlements, as some of these have been shown to be valuable as potential intermediary sites and/or to be centrally located on routes between other settlements. The settlement location analysis has found that settlements tend to concentrate on the levees in areas where settlements already existed previously and close proximity to transport networks. Other factor were less important, showing that the location of new settlements is mostly governed by landscape suitability and the potential to interact with other rural settlements, and not particularly to interact with the military population. These findings are valuable for archaeologists to further their thought on interactions between the local and military population of the Dutch *limes* area.

Of similar importance are the methods through which these results are achieved. By formulating the archaeological questions in such a way that they can be addressed by the computational approaches, these studies can provide new insights that were not readily extractable from the archaeological data beforehand. More specifically tailored to the approaches applied in this research, the application of LCP analysis to model local transport connections has proven valuable, as it allows for the inclusion of the natural terrain, and this was found to have significant impacts on following analyses. The application of network analysis on problems that are specifically suitable to be addressed as networks has proven to be valuable and lead to interesting archaeological conclusions, and the results of this research thus encourages similar future problems around transport to be addressed as networks as well. Important in the application of computational approaches is the need to account for uncertainty in the data and methods, and for the validation of the results. Archaeological data is inherently uncertain and incomplete, and quantitative approaches thus remain susceptible to such data problems; this research only shows some ways in which these uncertainties can be incorporated into the research to strengthen the output.

Samenvatting in het Nederlands

Hoofdstuk 1: Introductie

Het hoofddoel van deze studie als onderdeel van het grotere 'Finding the limits of the *limes*' project is het analyseren en reconstrueren van het cultuurlandschap van het Nederlandse *limes*gebied, in het bijzonder kijkende naar de site- en nederzettingspatronen, transportnetwerken en hun wederzijdse relatie met de natuurlijke omgeving.

Allereest moet het natuurlijke landschap precies in kaart zijn gebracht, om de ruimtelijke ontwikkelingen en patronen van het cultuurlandschap in relatie tot het natuurlijke landschap beter te begrijpen. Omdat het huidige project focust op zowel de Cananefaatse als de Bataafse *civitas*, is het eerste doel het uitbreiden van de bestaande reconstructies van het natuurlijke landschap over het gehele Nederlandse *limes*gebied. Echter bestaat er vanuit een methodologisch perspectief de bezorgdheid dat er impliciete en soms expliciete onzekerheden zitten in elke paleogeografische reconstructie. Een secundair doel is daarom zorg te dragen dat deze onzekerheden duidelijk en definieerbaar worden, en mogelijk om de invloed van deze onzekerheden in latere analyses te testen.

Een tweede doel van deze thesis is de reconstructie en analyse van transportnetwerken die actief waren in de regio. Daaruit voortvloeiend is het eerste aandachtspunt het kwantificeren en expliciteren van de factoren die transport reguleren, in termen van de actoren, de frequentie, het doel en de modus van transport, zowel als de rol van de natuurlijke omgeving die transport hindert of faciliteert. The resultaten hiervan kunnen gebruikt worden voor de reconstructie van transportnetwerken. De toepassing van netwerkanalyse op dergelijke gemodelleerde transportnetwerken kan ons helpen informatie uit de netwerken te onttrekken met betrekking tot archeologische vraagstukken zoals de hiërarchie van nederzettingen en de rol van individuale sites (zowel nederzettingen als Romeinse militaire sites) in het netwerk, wat vervolgens tegen het licht gehouden kan worden aan de hand van de archeologisch bekende gegevens.

Het derde doel van deze thesis is de analyse van individuele sites in het landschap. Uit de positie die een site inneemt in het landschap kan mogelijk informatie worden onttrokken over de factoren die een rol hebben gespeeld in de locatiekeuze van de site. Om dit te volbrengen, worden de sites eerst onderworpen aan een analyse van de individuele factoren voor locatiekeuze, en vervolgens aan een multivariate analyse. In deze laatste analyse worden alle mogelijke factoren in locatiekeuze tegelijk bekeken, waaruit informatie kan worden herleid met betrekking tot de belangrijkheid van individuele factoren, de onderlinge relatie tussen factoren of de variatie in sitedistributie die verklaard kan worden aan de hand van de geanalyseerde factoren.

Hoofdstuk 2: Natuurlijke paleogeografie

Dit hoofdstuk presenteert het werk dat is gedaan met betrekking tot de natuurlijke paleogeografie van het Nederlandse deel van de Romeinse *limes* binnen het 'Finding the limits of the *limes*' onderzoeksproject. Ten tijde van het begin van het project was nog geen een reconstructie van de natuurlijke paleogeografie van het Nederlandse *limes*gebied beschikbaar die geschikt is voor gedetailleerde kwantitatieve analyses. De enige beschikbare paleogeografische reconstructies voor het gehele onderzoeksgebied zijn te grootschalig voor zulke methoden. Projecten met gedetailleerde paleogeografische reconstructies zijn reeds uitgevoerd voor kleinere gebieden, zoals een project over west-Nederland in het eerste millenium en een project over de Romeinse *limes* in het Oude Rijngebied. Het werk uit dit laatstgenoemde project is opgenomen in het huidige onderzoek, en de methodologie van deze reconstructie is toegepast om de paleogeografische kaart uit te breiden over het gehele onderzoeksgebied.

Hoewel gedetailleerde paleogeografische reconstructies beschikbaar waren voor sommige delen van het Nederlandse *limes*gebied, is het analytische potentieel van zulke reconstructies nog niet volledig uitgebuit. De paleogeografische kaart van het Nederlandse *limes*gebied gedurende de Romeinse Tijd in het huidige onderzoek is gemaakt met de intentie om het te gebruiken voor ruimtelijke analyses, zoals het modelleren van routes, netwerkreconstructie, analyse van sitelocatie en modellen van agrarische productie.

Een verdere toevoeging aan dit werk dat tot dusver ondergewaardeerd is gebleven in paleogeografisch onderzoek is de expliciete erkenning van onzekerheid. Bij de paleogeografische reconstructie van het Nederlandse *limes*gebied in dit project is het expliciet maken van deze onzekerheid in het oog gehouden door middel van het ontwikkelen van onzekerheidskaarten en het vermelden van de verschillende bronnen van onzekerheid. Tijdens het gebruik van de paleogeografische kaarten voor ruimtelijke analyses en modelleren is het belangrijk om te weten waar de onzekerheid een rol speelt, omdat dit een invloed kan hebben op de resultaten van het onderzoek.

Hoofdstuk 3: De dataset van archeologische sites

Eén van de belangrijkste componenten van een regionale studie is een betrouwbare dataset van archeologische sites waarop analyses en interpretaties gebaseerd kunnen worden. Dit hoofdstuk presenteert de dataset van archeologische sites die is gebruikt in deze studie.

Het merendeel van de archeologische informatie in Nederland is geregistreerd in de nationale archeologische database ARCHIS, waar het is opgeslagen op het niveau van individuele observaties (in essentie gelijk aan vindplaatsen). Om te komen tot een archeologische site, moet dus een interpretatie gemaakt worden van de observatiegegevens. Eén observatie of meerdere observaties samen vormen in dit onderzoek een site op basis van gedefinieerde criteria. Het eerste criterium is het aantal vondsten in observaties binnen een bepaalde straal, hier gezet op 10. Het tweede criterium is die straal die wordt gebruikt om de observaties tot een site te groeperen, hier gezet op 250 m. Na het definiëren van een site op basis van één of meerdere observaties, is de volgende stap het toekennen van een interpretatie met betrekking tot het karakter van die site. In het algemeen volgt de classificatie van sites in dit project de structuur die is gehanteerd in eerdere studies in het Nederlandse deel van het Romeinse *limes*gebied. Nederzettingen worden onderverdeeld in militaire nederzettingen (inclusief *castra*, militaire kampen, *castella*, wachttorens en ongedefinieerde militaire nederzettingen) en niet-militaire nederzettingen (inclusief grotere civiele nederzettingen, rurale steenbouwnederzettingen en reguliere rurale nederzettingen).

Hoewel aan sommige sites (zoals de opgegraven Romeinse militaire sites) een relatief nauwkeurige datering kan worden toegekend, is voor het merendeel van de sites in de database slechts beperkt informatie beschikbaar op basis waarvan de chronologie kan worden bepaald. In plaats van exacte tijdspannen, werden de sites daarom gedateerd aan de hand van de archeologische perioden die worden gebruikt in de ARCHIS-database. Met deze methodologie kan de kwaliteit en precisie van de datering echter sterk variëren binnen de dataset, wat mogelijk invloed heeft op latere analyses. De chronologische informatie die is geassocieerd met de observaties in de ARCHIS-database is daarom gebruikt om de dateringen van de archeologische sites te herinterpreteren. Hiervoor is een Monte Carlosimulatiemethode toegepast waarin het aantal vondsten in een periode is berekend per simulatie gebaseerd op aanwezigheidskansen. Gebaseerd op de eerdere aanname dat een site bestaat als er minstens 10 vondsten aanwezig zijn op die locatie, kan de aanwezigheidskans van een site worden bepaald per tijdsperiode op basis van het aantal simulaties waarin 10 of meer vondsten tegelijk bestaan. Deze waarden kunnen worden gebruikt in latere (ruimtelijke analyses), omdat een dataset van sites kan worden geconstrueerd die is gebaseerd op aanwezigheidskansen gedurende een tijdsperiode, in plaats van de originele dataset met chronologische informatie van variërende kwaliteit en precisie.

Hoofdstuk 4: Het karakteriseren van transportsystemen in het Nederlandse deel van de Romeinse *limes*

Eén van de doelen van deze studie is het reconstrueren en analyseren van de transportnetwerken die actief waren in de regio, ten eerste door het identificeren en kwantificeren van de regulerende factoren van transport in het algemeen en de verplaatsing van goederen in het bijzonder. Dit hoofdstuk heeft betrekking op de karakterisatie van transport, in het bijzonder voor het Nederlandse deel van de Romeinse *limes*.

Transport is de subset van beweging of mobiliteit waarin mensen, dieren, goederen of informatie worden getransporteerd tussen twee locaties. Allereest moet een belangrijk onderscheid gemaakt worden op basis van de schaal van transportbewegingen. Drie samenhangende netwerken kunnen worden onderscheiden: een imperiaal uitwisselingsnetwerk, interprovinciale uitwisselingsnetwerken en regionaal gecentreerde, provinciale uitwisselingsnetwerken. De primaire interesse van deze studie ligt in het transport binnen de grenzen van het onderzoeksgebied, en in het bijzonder transport tussen de lokale en de militaire bevolking. Het eerste niveau hier heeft betrekking op interregionaal transport, waarmee wordt bedoeld de verplaatsing van goederen of personen over grotere afstanden (over de grenzen van de *civitas*), maar nog binnen de regio van het onderzoeksgebied, de Bataafse en Cananefaatse *civitates*. Het tweede niveau betreft het regionale transport, het transport binnen de *civitas*. Het laagste niveau van transport betreft het transport over korte afstanden, het transport ok lokale schaal. Een voorbeeld hiervan is het transport van goederen van nederzettingen naar lokale markten, waarvan de meerderheid waarschijnlijk bestaat uit agrarische surplusproductie.

Het doel van transport kan variëren. Onmiddellijk herkenbare doelen zijn transport onder invloed van economische marktwerking, sociale interactie, politieke representatie of militaire acties. Economisch transport, wat normaal gesproken het transport van goederen tussen productie-, markt- en consumptiesites betreft, is waarschijnlijk het meest frequent bestudeerde en meest kwantificeerbare aspect van transport. Een groot deel van de transportbewegingen in het onderzoeksgebied moet waarschijnlijk op zijn minst deels economisch van aard zijn geweest. De integratie van het Nederlandse rivierengebied in het Romeinse Rijk heeft nieuwe lasten opgelegd aan de lokale bevolking, zoals belasting, wat zou kunnen bestaan uit het afstaan van surplusproductie (of mankracht aan het Romeinse leger in de Vroeg-Romeinse Tijd) of in de vorm van geld dat is verkregen uit de verkoop van goederen op lokale markten. De nieuw ontstane economie met voor die tijd ongekende vraag- en aanbodstructuren moet het aantal en de grootte van transportbewegingen hebben vergroot, in het bijzonder het transport van voedingsmiddelen van productiesites naar markt- en consumptiesites.

De militaire en lokale bevolking van de Rijn-Maasdelta hebben een aantal transportmodi tot hun beschikking gehad, elk met specifieke karakteristieken. Deze modi van transport waren ook niet altijd wederzijds exclusief: ze hebben waarschijnlijk gefunctioneerd as onderdeel van een complementair systeem. In dit hoofdstuk wordt een overzicht gegeven van gegevens uit de beschikbare literatuur met betrekking tot de verschillende transportmodi. Voor wat betreft landtransport, in het bijzonder lokaal transport in het Nederlandse *limes*gebied, is de meest voorkomende transportmethode waarschijnlijk te voet. Transport met behulp van dieren is ook beschikbaar geweest in het Nederlandse deel van de Romeinse *limes*. Dit zal voornamelijk gebruik hebben gemaakt van ossen, omdat paarden niet vaak zijn gebruikt als last- of trekdieren, en muilezels in de regio moeten worden geïmporteerd. Vier verschillende vaartuigen worden behandeld in het overzicht van watertransport, namelijk platbodems, punters, galleien en boomstamboten. Galleien zullen primair als militair vaartuig zijn gebruikt en over punters is weinig bekend omdat er slechts één is gevonden in het Nederlandse rivierengebied. Platbodems zijn het meest iconische type van watertransport in het Nederlandse deel van de Romeinse *limes*, gebruikt voor het bulktransport van zwaar bouwmateriaal en lichtere goederen zoals koopwaar. Boomstamboten kunnen daarentegen worden gezien als representatief voor watertransport op lokalere schaal. Ze zijn een continuatie van lokale tradities van varen en waren continu in gebruik, zelfs in de aanwezigheid van de grotere platbodems.

Met behulp van de informatie die is gepresenteerd in dit hoofdstuk is het duidelijk geworden dat het begrip over transport in de Romeinse Tijd best goed is voor wat betreft transport dat plaatsvindt op bovenregionale schaal, door de beschikbaarheid van zowel archeologische informatie als geschreven bronnen en een lange onderzoekstraditie. Er is echter veel minder bekend over transport op lokale en regionale schaal, waaronder de interactie tussen de lokale en militaire bevolking in het Nederlandse deel van de Romeinse *limes*. Voor een belangrijk deel is dit het resultaat van het feit dat transport op deze schaalniveaus niet wordt benoemd in geschreven bronnen en zeer weinig sporen in het archeologische bodemarchief achterlaat.

Hoofdstuk 5: Transportverbindingen modelleren

Omdat de interesse van de huidige studie voornamelijk ligt in transport op de locale schaal in het Nederlandse deel van het Romeinse *limes*gebied (als onderdeel van het complex aan schalen waarop transport kan hebben plaatsgevonden), is er slechts zeer beperkt archeologisch materiaal bruikbaar als gevolg van het immateriële karakter van lokale transportbewegingen. Het gebrek aan vondstmateriaal voor een alledaagse activiteit zoals beweging door een landschap is een bekend fenomeen in archeologie, en reeds sinds enige tijd worden computationele methoden gebruikt om patronen van beweging te bestuderen. De focus van dit hoofdstuk is daarom op de verschillende aspecten van het modelleren van transport in het Nederlandse deel van de Romeinse *limes* met behulp van optimale routeanalyse (*least-cost path analysis*).

De belangrijkste beslissing die moet worden gemaakt tijdens het modelleren van optimale routes voor transport te voet is het bepalen van de kosten die worden meegewogen in de analyse. Van de verschillende functies die beschikbaar zijn voor het berekenen van de kosten van beweging, is de formule van Pandolf *et al.* (1977) verkozen vanwege de mogelijkheid om coëfficiënten gerelateerd aan het terrein en getransporteerde ladingen te gebruiken. In tegenstelling tot het modelleren van de kosten van transport te voet, waarvoor veel fysiologische en/of experimentele functies beschikbaar zijn, is er veel minder onderzoek gedaan naar het modelleren van de tijds- of energiekosten van transport met behulp van dieren. In plaats daarvan is gebruik gemaakt van een combinatie van functies die de tractiekracht over verschillende terreinen kan berekenen. Naast landtransportmodi hebben de lokale en militaire bevolking in het Nederlandse deel van het Romeinse *limes*gebied ook beschikking gehad over watertransportmodi. In deze studie is watertransport met boomstamboten gemodelleerd als onderdeel van multimodale routes. In het algemeen is de berekening van een optimale route van een multimodale transportverbinding gelijk aan die van een unimodale landtransportverbinding. Het enige verschil zit in de kosten van beweging over rivieren en beken, die in dit geval watertransport accommoderen in plaats van een barrière voor beweging vormen.

Het in dit hoofdstuk gepresenteerde modelleren van transportverbindingen is succesvol in termen van het begrip van de relatie tussen beweging en de natuurlijke omgeving, en het realiseren van die relatie in de constructie van optimale routes. Het resultaat laat een merkbaar verschil zien tussen de gemodelleerde routes van transport te voet en transport met trekdieren in termen van waar men beweegt met deze transportmodi, en een verdere variatie is geïntroduceerd met het gebruik van boomstamboten. Het modelleren van transport te voet is echter uitgevoerd met meer zekerheid vanwege de sterkere basis in fysiologisch (en archeologisch) onderzoek, terwijl landtransport met behulp van dieren en watertransport een minder sterke en minder compatibele basis aan bronnen hebben voor de situatie van het Nederlandse rivierengebied.

Tussen categorieën van transport te voet of transport met trekdieren is een verder verschil in termen van de reistijd. Dit is belangrijke informatie wanneer wordt doorgedacht in termen van transportnetwerken, waarin tijd een rol kan spelen in de bepaling of een gemodelleerde transportverbinding onderdeel uitmaakt van het netwerk. Hoewel op basis van de gemodelleerde routes preliminaire beweringen kunnen worden gemaakt, zoals de observatie dat de Romeinse militaire weg langs de Rijn geen rol heeft in lokale transportverbindingen vanwege zijn perifere locatie, kunnen ze niet meteen iets zeggen over het functioneren van transportsystemen in de Romeinse Tijd wanneer het betrekking heeft op vraagstukken zoals de verspreiding van surplusproductie vanuit rurale nederzettingen en de bevoorrading van het Romeinse leger. Dit vereist een verdere interpretatie en analyse, wat kan worden uitgevoerd in de context van transportnetwerken.

Hoofdstuk 6: Transportnetwerken in het Nederlandse deel van de Romeinse *limes*

Het doel van dit hoofdstuk is de bestudering van lokale transportnetwerken in het NEderlandse deel van de Romeinse *limes* met gebruik van concepten uit de netwerkwetenschap. In elke sectie van dit hoofdstuk worden één of meerdere problemen geïdentificeerd, waaronder zowel methodologische als archeologische vraagstukken, waarna een aanpak wordt gezocht die op deze problemen kan worden toegepast.

Allereest wordt in sectie 6.2 een vergelijking gemaakt tussen verschillende netwerkconstructietechnieken, om een netwerkstructuur te identificeren die het dichtst bij de te representeren archeologische werkelijkheid komt. Dit is een noodzakelijke stap die genomen moet worden om van een dataset van potentiële transportverbindingen gemodelleerd op basis van optimale routes te komen tot een netwerk die kan worden geanalyseerd met behulp van concepten uit de netwerkwetenschap. Door het opstellen van archeologisch relevante evaluatiecriteria, bijvoorbeeld hoe eenvoudig het is om goederen te verplaatsen van rurale nederzettingen naar *castella*, wat meetbaar is door de gemiddelde padlengte in het netwerk, kan een kwantitatieve evaluatie worden gemaakt van verschillende netwerkconstructietechnieken. In dit geval blijkt de Gabrielgrafiek de meest representatieve netwerkstructuur te zijn van een lokaal transportnetwerk voor de distributie van goederen vanuit de lokale bevolking naar de militaire bevolking, maar evenzo belangrijk, wordt in deze sectie een aanpak gedemonstreerd van hoe een dergelijk methodologisch probleem kan worden geadresseerd met de archeologische realiteit in ogenschouw.

De toepassing van netwerkanalysetechnieken op archeologische netwerken leidt ook tot vragen over onzekerheid: hoe afhankelijk zijn de resultaten bijvoorbeeld van de compleetheid van de dataset? In sectie 6.3 worden de effecten van onzekerheid op de resultaten van netwerkanalyse onderzocht, door middel van het construeren van een model die iteratief netwerken bouwt vanuit de bestaande datasets, zodat van netwerkmetingen de afhankelijkheid kan worden bepaald van de compleetheid van de netwerkstructuur. Het blijkt dat 64% van de sites een robuuste meting hebben, wat betekent dat de resultaten niet afhankelijk zijn van die specifieke netwerkstructuur maar hetzelfde blijven wanneer bijvoorbeeld sites missen of foutief aanwezig zijn in de dataset. Aan de andere kant is het voor 36% van de gevallen dus niet betrouwbaar, en dit moet meegewogen worden bij de toepassing van netwerkanalyse op archeologische datasets. Een belangrijk aspect van deze studie is dat het een methodologie laat zien waarmee een dergelijk vraagstuk over onzekerheid in het licht van de archeologische datasets kan worden geadresseerd.

Sectie 6.4 focust op de toepassing van netwerkanalyse op de gemodelleerde transportnetwerken. De eerste casus test een archeologische hypothese die stelt dat de (re)distributie van goederen in het Nederlandse deel van de Romeinse *limes* werd gerealiseerd door een hiërarchisch dendritisch systeem, waarin intermediaire sites functioneerden tussen de militaire bevolking in de *castella* en de lokale bevolking in de rurale nederzettingen. Deze hypothese is getest door het contrasteren van twee hypotheses: een nulhypothese waarin alle surplusgoederen direct naar de *castella* worden vervoerd, en een alternatieve hypothese waarin goederen eerst worden verplaatst naar vooraf bepaalde intermediaire sites voordat ze als bulkgoederen naar de *castella* worden vervoerd. De netwerkmeting padlengte (wat in deze studie gelijk staat aan de reistijd) is gebruikt om deze hypotheses te evalueren, en hieruit blijkt dat in de meeste gevallen distributie via een intermediaire site efficiënter is dan een directe distributie, wat de alternatieve hypothese die is gesteld in eerdere archeologische studies waarschijnlijker maakt dan de hier gestelde nulhypothese, hoewel er ook ruimte is voor een duaal systeem waarbij beide distributiemethoden in samenhang functioneerden. Deze studie is een goed voorbeeld van hoe een archeologisch idee kan worden getest en dus meer waarde kan worden gegeven door het uitwerken van het probleem in expliciete hypotheses die kunnen worden geëvalueerd met behulp van concepten uit de netwerkwetenschap.

De tweede casus in sectie 6.4 gaat dieper in op de rol van rurale steenbouwnederzettingen. In het bijzonder wordt de vraag gesteld of deze rurale steenbouwnederzettingen een potentiële controle hadden over transportbewegingen in het netwerk dat ervoor kan hebben gezorgd dat ze belangrijker werden door de tijd heen, wat een eigenschap is die kan worden geëvalueerd met behulp van de netwerkmeting van tussencentraliteit (*betweenness centrality*). Hieruit blijkt dat een aantal rurale steenbouwnederzettingen een hogere tussencentraliteit hebben dan de gemiddelde nederzetting in hun omgeving, en dat dit aantal hoger is dan zou worden verwacht op basis van de ratio van het aantal rurale nederzettingen die steenbouw hebben. Het is opmerkelijk dat dit voor de meeste steenbouwsites al reeds het geval is in de Late IJzertijd of de Vroeg-Romeinse Tijd, dat wil zeggen in de pre-steenbouwfase van deze nederzettingen. Dit kan een indicatie zijn dat de reden dat deze nederzettingen belangrijk zijn geworden en uiteindelijk steenbouw verkregen hebben deels kan liggen in de potentiële controle die ze hebben over transportbewegingen in het netwerk. Deze casus is een goed voorbeeld van hoe netwerkmetingen kunnen worden gebruikt om de individuele rol van nederzettingen in transportnetwerken te bestuderen.

In sectie 6.7 wordt de geherinterpreteerde chronologische informatie, opgesteld volgens de methodologie beschreven in Hoofdstuk 3, gebruikt om de continuïteit en veranderingen in transportnetwerken door de tijd heen te testen. Het blijkt dat de applicatie van deze nieuwe chronologische informatie geen significante verandering uitoefent op de resulterende netwerkstructuren vergeleken met de originele chronologie, wat een belangrijke conclusie is omdat anders de resultaten van analyses alleen afhankelijk zouden zijn van de gebruikte chronologie. In plaats daarvan kan de geherinterpreteerde chronologie gebruikt worden om de veranderingen door de tijd heen te bestuderen met meer chronologische betrouwbaarheid. Deze studie laat zien dat er een hoge mate van continuïteit is in lokale transportnetwerken, en dat deze continuïteit groter is dan zou worden verwacht op basis van de continuïteit in de nederzettingen, wat een indicatie is dat lokale transportnetwerken persistenter zijn dan het nederzettingspatroon. Er zijn ook sommige variaties zichtbaar in de mate van continuïteit, wat gerelateerd kan worden aan bekende perioden van instabiliteit zoals de Bataafse Opstand en de val van de rijksgrens in de 3de eeuw.

Hoofdstuk 7: Analyse van sitelocatie

In dit onderzoek heeft sitelocatie om meerdere redenen de interesse: om te bepalen wat de (natuurlijke, culturele/sociale of historische) regulerende factoren van de locatiekeuze van nederzettingen zijn, om de ontwikkeling van nederzettingspatronen door de tijd heen te bestuderen, en om inputdata voor modellen van agrarische productie te genereren. De analyses in dit hoofdstuk bestaan ten eerste uit een analyse van de individuele factoren (inclusief de natuurlijke paleogeografie, rivieren en beken, forten, transportnetwerken, potentiële intermediaire sites in transportnetwerken, en de invloed van het historische landschap), en ten tweede uit een multivariate aanpak om de relatieve invloed van factoren te bestuderen en hoe dat mogelijk verandert door de tijd heen. Deze laatste analyse gebruikt een Monte Carlosimulatiemethode om een logistisch regressiemodel te ontwikkelen dat de aan- of afwezigheid van een site voorspelt per tijdsperiode.

De resultaten laten zien dat het historische landschap en de afstand tot transportnetwerken belangrijke factoren zijn voor nederzettingslocaties, wat indiceert dat het gebruik van culturele/sociale factoren zoals het historische landschap en de gemodelleerde transportnetwerken een waardevolle impact hebben op een studie naar nederzettingslocaties. Enkele interessante verschuivingen zijn te zien in de voorkeuren voor nederzettingslocaties door de tijd heen, met een verschuiving naar meer ‘marginale’ gebieden in de Vroeg-Romeinse Tijd A-B en Midden-Romeinse Tijd A-B intervallen, zowel in termen van de natuurlijke omgeving als het nederzettingslandschap. Dit kan mogeijk het resultaat zijn van een verandering in de modi van productie of van een stijgende druk in de kern van het bewoningsgebied op de rivieroeverwallen. Een tegengestelde verschuiving is te zien in het Laat-Romeinse Tijd A-B interval, waarin nieuwe nederzettingen juist primair gesitueerd zijn binnen de kern van het bewoningsgebied in plaats van aan de marges, wellicht omdat een lagere populatiedruk deze verhuizing niet noodzakelijk maakte.

Hoofdstuk 8: Synthese / Hoofdstuk 9: Conclusie

Deze hoofdstukken presenteren de resultaten van dit deel van het ‘Finding the limits of the *limes*’ project, en plaatsen ze in de wijdere onderzoekscontext. Het doel is om een samenvatting en uiteenzetting te maken van enkele innovatieve aspecten van deze studie, vanuit technische, methodologische of interpretatieve perspectieven. Om dit te doen worden in Hoofdstuk 8 enkele casussen gepresenteerd uit dit onderzoek op het gebied van transportnetwerken en neerzettingslocatie in het Nederlandse deel van de Romeinse *limes*. Geformuleerd in een meer algemene vraag, het doel van Hoofdstuk 8 is als volgt: wat heeft deze ruimtelijk analytische studie van het cultuurlandschap van het Nederlandse *limes*gebied bijgedragen aan het onderzoeksveld van computationele archeologie en gerelateerde velden, en wat heeft het bijgedragen aan de archeologische kennis over het Nederlandse deel van de Romeinse *limes*?

Het modelleren van optimale routes, de netwerkstudies en de analyse van nederzettingslocatie gepresenteerd in deze studie hebben enkele nieuwe en waardevolle inzichten gebracht in de eigenschappen van beweging op lokale schaal in de Nederlandse Rijn-Maasdelta, het potentiële functioneren van het Romeinse lokale bevoorradingssysteem, de rol van individuele sites binnen deze lokale transportnetwerken, en de relatie van nederzettingen met hun natuurlijke en sociale omgeving. Uit de studies op de gemodelleerde transportnetwerken blijkt bijvoorbeeld dat in ieder geval voor de oostelijke en centrale delen van het onderzoeksgebied het waarschijnlijker is dat transport van de lokale bevolking naar de militaire bevolking werd uitgevoerd via intermediaire sites in plaats van direct naar de forten, wat de bestaande archeologische hypothese van een dendritisch hiërarchisch nederzettingssysteem ondersteunt. Verder blijkt dat de rol van individuele nederzettingen in deze transportnetwerken kan hebben geleidt tot de ontwikkeling tot rurale steenbouwnederzettingen, omdat sommige van deze nederzettingen en waardevolle rol kunnen hebben vervuld als potentiële intermediaire sites en/of centraal gelegen waren tussen andere nederzettingen. De analyse van nederzettingslocaties laat zien dat de nederzettingen zich concentreerden op de rivieroeverwallen in gebieden waar oudere nederzettingen zich reeds bestonden en in de nabijheid van transportnetwerken. Andere factoren waren minder belangrijk, wat laat zien dat de locatie van nieuwe nederzettingen grotendeels bepaald werd door de geschiktheid van het landschap en het potentieel voor interactie met andere rurale nederzettingen, en in het bijzonder niet met de militaire populatie. Deze bevindingen zijn waardevol voor archeologen met betrekking tot de huidige kennis over interacties tussen de lokale en de militaire bevolking in het Nederlandse *limes*gebied.

Net zo belangrijk zijn de methoden waarmee deze resultaten zijn bereikt. Door de archeologische vraagstukken zo te formuleren dat ze getest kunnen worden met computationele technieken, kunnen deze studies nieuwe inzichten produceren die niet panklaar uit de archeologische data gehaald kunnen worden. Specifiek voor wat betreft de gebruikte methoden in deze studie, heeft de toepassing van optimale routeanalyse laten om transportverbindingen te modelleren laten zien waardevol te zijn omdat het rekening houdt met het natuurlijke landschap, wat een significante impact had op de later analyses. De toepassing van netwerkanalyse op problemen die bij uitstek geschikt zijn om als netwerken behandeld te worden heeft laten zien te leiden tot waardevolle en interessante archeologische conclusies, en de resultaten van dit onderzoek moedigen dus ook aan tot de toepassing van netwerkmethoden op vergelijkbare archeologische problemen in de toekomst. Belangrijk in de toepassing van computationele technieken is het erkennen van de onzekerheid in de data en de methoden, en de validatie van de resultaten. Onzekerheid en incompleetheid zijn inherent aan archeologische data, en kwantitatieve methoden blijven dus vatbaar voor zulke problemen; dit onderzoek laat slechts enkele manieren zien waarmee deze onzekerheden in het onderzoek opgenomen kunnen worden en daarmee de uitkomsten van het onderzoek kunnen versterken.