Living along the *Limes*

Landscape and settlement in the Lower Rhine Delta during Roman and Early Medieval times

Leven aan de *Limes*

Landschap en bewoning aan de Oude Rijn
tijdens de Romeinse Tijd en Vroege Middeleeuwen

(met een samenvatting in het Nederlands)

Proefschrift

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Utrecht 2017

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Kwartair Geoloog
Een opgeschaafde
profielwand
is een vorm
van geluk

(vrij naar Emo Waterland; bron: Grondtonen; gedichten over archeologie, 2008)

I was told that my grandfather was already interested in geography. Unfortunately, he died before I was born. Maybe I inherited his enthusiasm. During my youth, my parents took me all over Europe during holidays and I learned to realize and value the different landscapes and cultures. Only during my first geological fieldwork in the Rhine-Meuse delta – under the supervision of Henk Berendsen (†) – I realised the presence of buried landscapes below my feet and the fact that our ancestors lived in those hidden landscapes. It would not have been possible to finish this thesis without the help of many. I want to thank you all for your contribution, whether it was professional or as a friend.

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Marieke

1 Introduction

River environments have played a vital role in human history. Alluvial landscapes comprise ecologically rich and varied environments, thereby providing an attractive environment for humans and other hominids (Hill, 2014). They provide abundant natural resources for exploitation, settlement locations, and transportation networks (Howard and Macklin, 1999).

River deltas are, therefore, long since inhabited, and the roots of our modern civilisation, such as in Mesopotamia, Egypt, India, and China, lie on the banks of some of the great rivers of the world. Here, civilizations arose primarily owing to the fertile flood plains soils that allowed cultivation of cereals. As a result, these societies were able to produce more food than was needed for their subsistence, allowing a substantial part of the population to devote their time and energy to other activities, such as crafts, and intellectual and artistic tasks. The Mesopotamian and Egyptian civilizations arose in the eastern Mediterranean, in the so-called *Fertile Crescent*. Mesopotamia ('land between rivers' – Tigris and Euphrates) is renowned for its impressive record of past human activity, holding not only many sites with archaeological remains of both pre-modern and early-modern humans, but is most famous for sites related to the origin of agriculture through the domestication of wild cereals (e.g. Zohary and Hopf, 2000; Tanno and Willcox, 2006; Luo *et al.*, 2007; Wilcox, 2012; 2013). Human settling started here already c. 10,000 BC, when ancient hunter-gatherers turned to sedentary agriculture. During the 4th millennium BC the first cities arose here, concurrent with the invention of handwriting, giving rise to a well-developed early civilisation. Similar developments occurred in societies arising along the Nile River and delta in Egypt, the Indus valley, and along the Yellow River in China (e.g. Bard, 2015; Wright, 2010 resp. Zhuang and Kidder, 2014). Therefore, these areas are commonly considered as the 'cradle of civilization'.

Millennia after the arrival of these early settlers, river areas and deltas have become intensively colonised and exploited by humans, and at present they support over 500 million people worldwide. However, the intensive exploitation of rivers and deltas has increasingly caused problems, particularly in deltas. Extraction of natural resources and groundwater and the construction of dikes and dams have induced land subsidence and water pollution resulting in flooding, land degradation, and loss of ecosystems (e.g. Syvitsky *et al.*, 2009; Vörösmarty *et al.*, 2009). Furthermore, river flood plains and deltas are threatened by climate change and sea-level rise. In response, sustainable management programmes are being developed for deltas globally to ensure sustainable future delta life. Regulations and management policies are designed and explored to prevent or restore subsidence and to improve drinking-water quality and supply by urban and rural development, water management, and nature conservation directed at preventing and restoring damages. This shows that adaptive delta management has become a hot topic (Van der Most *et al.*, 2009; Bucx *et al.*, 2010; Haasnoot *et al.*, 2013; www.deltacommissaris.nl). Solving the current problems not only requires understanding of the river system, and designing engineering structures. It also requires a more fundamental understanding of how natural and societal systems interact.

Such interactions certainly already occurred during first occupation of the at that time still natural deltas, since the earliest settlers already had to deal with natural changes and delta dynamics, such as river flooding and changes of the river courses. This raises questions such as 'how did these societies adapt to the specific problems and restrictions imposed by nature in these wetland areas, did they respond to these changes and dynamics by changing their occupancy pattern, and did they already try to prevent change in the natural environment by intervening? Answering these questions would be a first and important step in the process of increasing our understanding of the interaction between social and natural systems in deltas.

The Rhine-Meuse delta in the Netherlands is one of the densely-populated and heavily-engineered deltas with a long settlement history, for which the Roman Period (12 BC – 450 AD) was a crucial time-interval when it comes to the relation between the social and natural delta systems. During this period, a distributary of the river Rhine functioned as the northern border of the Roman Empire, and a series of military structures was built along this river branch. The soldiers in this area lived together with local inhabitants on the levees in-between swampy wetlands. They were among the first to intervene in the delta landscape, not only through the construction of dams (*Moles Drusi* in Tacitus' *Historiae* V,19 and Tacitus' *Annales* XIII, 53), culverts (De Ridder, 1997; 1999; 2001), canals (*Fossa Corbulonis* in Tacitus"*Annales* XI,18-20 and Cassius´ Dio *Historia Romana* LXI 61 30: 4-6.; e.g. De Kort and Raczynski-Henk, 2014; and *Fossa Drusiana* in Tacitus"*Annales* II, 8 and Suetonius' *Vita divi Claudii* 1.2), and swamp bridges, moorings and landings stages, but also through the introduction of large-scale and systematic ditch systems for land division (e.g. Van Londen, 2006; Vos, 2009).

In the Mediterranean area, water management was practiced already far before the start of the Roman Period, maturing into well-developed water-management practice around the start of this period, comprising reservoirs, aqueducts, cisterns and community distribution systems across the Roman Empire (Frontinus' *De Aquis Urbis Romae*; Vitruvius' *De Architectura*). However, the dynamic environment in the deltas of the Empire required a specific water management approach, adapted to the dynamic nature of rivers and the deltas.

During the last decades, a wealth of (geo)archaeological information has become available in the Netherlands, owing to the many archaeological excavations and research projects that have been conducted in the Dutch delta, especially along major new infrastructure lines and near Utrecht where a new 25 km^2 large residential area 'Leidsche Rijn' was established. These studies have yielded large quantities of unique information about Roman settlement and land use in the delta. Yet, these studies mainly focused on the archaeological development and landscape reconstruction of the individual sites, and on the effect of environmental change on human activity on a local scale. Analysis and integration of the results to a regional scale still remain to be undertaken, which currently hampers systematic documentation and understanding of the interaction between the inhabitants and the dynamic river delta environment. Combining these local archaeological and environmental data and integrating them with the existing high-resolution database of the development of the Rhine-Meuse delta will be the first step needed to answer questions such as: where did settlements arise in the landscape; what were the abiotic settlement factors; why did the Romans build their military installations as a linear defence system at local and regional scale; and, more fundamentally: what was the relationship and interaction between human occupation and the natural environment of the delta in this early settlement period?

1.1 Archaeology in deltas

Geoarchaeology
The scientific discipline that encompasses the empirical study of the long-term relationship between humans and the physical (abiotic) and biological settings they inhabit is called 'Environmental Archaeology' (Fig. 1.1; e.g. Butzer, 1982; Evans, 2003; Wilkinson and Stevens, 2003; Branch *et al.*, 2005; O'Connor and Evans, 2005; Reitz and Shackley, 2012; Hill, 2014). The objective of environmental archaeology is to determine and understand the relations between past ecosystems and humans (e.g. Butzer, 1982; Shackley, 1985; Rapp and Hill, 1998; Evans, 2003; Wilkinson and Stevens, 2003; Branch *et al.,* 2005; O'Connor and Evans, 2005; Hudson *et al.,* 2008; Reitz and Shackley, 2012; Hill, 2014). To this end, geomorphological and other natural science approaches are deployed along with archaeology to investigate human-environment interactions (Butzer, 1982). More specifically, the subfield of geoarchaeology – or archaeological geology (Canti, 2001) – provides a means for examining physical settings, stratigraphic contexts, and site formational processes (e.g. Davidson and Shackley, 1976;Brown, 1997; Waters,1992; Rapp and Hill, 1998; Ferring, 2001; Goldberg and Macphail, 2006; Reitz and Shackley, 2012; Hill, 2014). This latter approach has been adopted in this thesis. Since cultural systems are inextricably linked to their environments (Reitz and Shackley, 2012), understanding these systems requires knowledge of the natural development and dynamics of the landscape, including its substrate and the vegetation that surrounded archaeological sites. Only in this manner, it becomes possible to understand how settlement dynamics and changes in land use adapted to landscape dynamics, and to what extent these in turn influenced the landscape.

The relation between humans and river environments can be studied at various scales in time and space, providing an understanding of the short-term and long-term sequence of events within an archaeological site and its landscape context (Hill, 2014). By focusing on processes of environmental change at landscape level, geoarchaeological research results in causal explanations of such changes and in interpretations of the consequences of these changes for cultural institutions (Reitz and Shackley, 2012).

Despite their variety, riverine environments show similar features in terms of hydrology, geomorphological processes and resulting landforms. An idealised river system includes a channel,

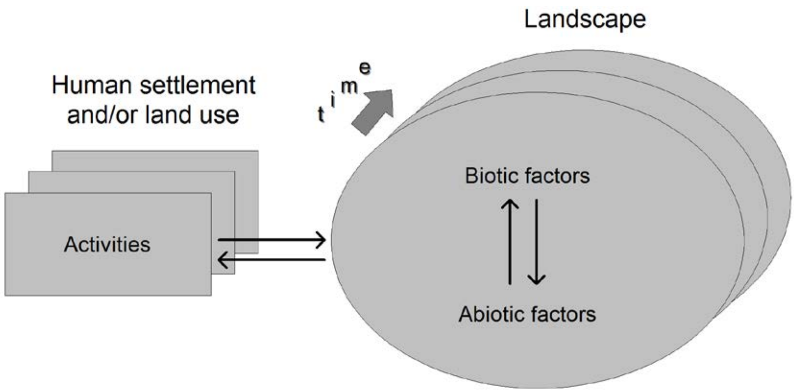

Figure 1.1 Schematic view of human-environment interactions through time.

a flood plain, and (a sequence of) terraces above the flood plain (e.g., Macklin and Howard 1999; Howard *et al.,* 2015; Bridgeland *et al.,* 2015). Lowland deltas with vertical aggradation constitute a peculiar situation, as they do not form river terraces. The alluvial ridges rise only slightly above the flood basin, predisposing settlements and agriculture land on the levees to periodic inundations. Furthermore, rivers in lowland deltas perpetually change their courses and networks owing to avulsions, creating new and abandoning older channels. Aggradation and concurrent human use of the delta create fluvial archives of alluvial ridges and channel belts with an embedded archaeological record. The changes in the location of river channels in the past may have had a considerable impact on settlement location and land use. Depending on the width of a delta, rates of aggradation, and river migration, the fluvial archive may be covered and/or partly reworked (e.g. Mackey and Bridge, 1995; Törnqvist and Bridge, 2002; Stouthamer and Berendsen, 2007; Hobo, 2015). The degree of reworking influences the possibilities for delta-evolution reconstructions, as well as the preservation potential and interpretation of archaeological sites. In terms of site-formation processes, the artefacts within a site are in *primary* context when the habitation surfaces are buried by overbank deposits. Artefacts found within levee and point-bar deposits appear to have been transported and redeposited and are, therefore, archaeologically in *secondary* context. Therefore, one goal of alluvial geoarchaeology is to account for the basic geomorphic processes that impacted individual archaeological sites as well as their surrounding landscapes (Hill, 2014).

1.2 Archaeology of Roman Empire deltas

Several river deltas were incorporated within the Roman Empire, including the deltas of the Nile, Danube, Rhône, Po, and Rhine-Meuse rivers (Fig. 1.2). In all these deltas geoarchaeological research has been undertaken, which is briefly discussed below.

Nile delta

The Nile delta in Egypt is one of the world's earliest recognised deltaic systems. However, only a few investigations have been published about this river's lower stretch and its distributaries, which once extended to the coast, and surprisingly little is known of the Holocene hydro-morphological development of this delta (Coutellier and Stanley, 1987; Butzer, 2002; Stanley and Warne, 1993; Stanley *et al.,* 2004; Flaux *et al.*, 2013; Marriner, *et al.,* 2012; 2013; Macklin *et al.,* 2015). In addition, a large number of fluvial units in the Nile Delta still remains to be dated (Macklin *et al.,* 2016).

Nevertheless, it is clear that the location of the Nile channels and their associated levees was a major factor in ancient settlement placement, as the river courses provided major arteries for transport (Trampier *et al.,* 2013). Furthermore, most sites were situated within or on the edge of an agricultural basin, since the farmers were dependent on flood water. Macklin *et al.* (2015) have presented the first catchment-scale meta-analysis of the Holocene river dynamics of the Nile resulting in the identification of major changes in river flow and dynamics in the Nile catchment between c. 6150 cal. BC and cal. AD 1600. These authors also discussed the impacts of changing hydro-morphological regimes upon riverine civilisations in the Nile Valley. During the Early Ptolemaic period (332-30 BC) and the Roman period (30 BC – AD 395), the frequency of overbank flooding decreased. However, there occurred a period of exceptional flooding around 100 cal. BC. The impact of this flooding on floodwater farming and settlement dynamics remains unresolved. The lack of data on the stratigraphy and chronology of the Nile delta prevents establishing a detailed palaeogeographic reconstruction of this river and delta during the Holocene, limiting our

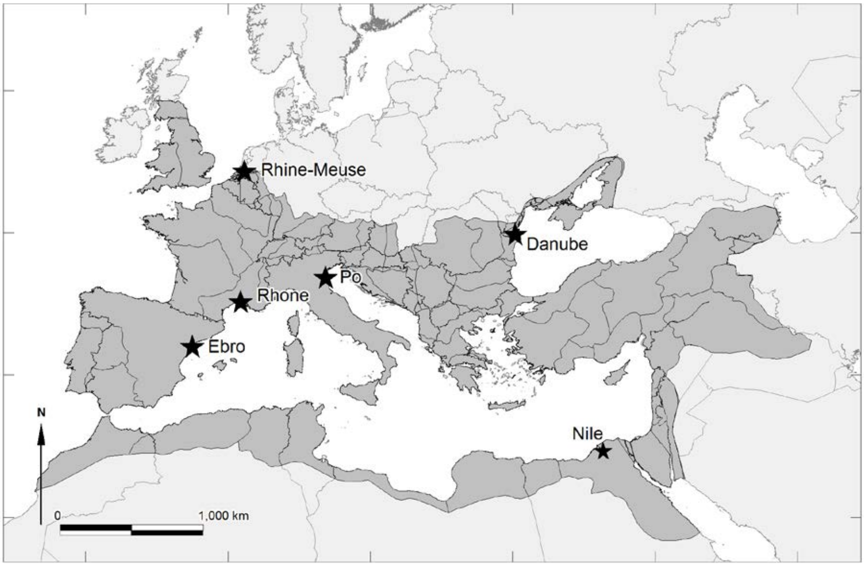

Figure 1.2 Maximum extent of the Roman Empire with the locations of the deltas discussed in the text.

understanding of the manner in which natural changes in this delta affected human settlement, and of the ways in which humans responded to these changes (Macklin *et al.*, 2015).

Danube delta

The Danube delta is Europe's second largest delta. Its palaeogeography and chronology have been reconstructed at delta scale (Ghenea and Mihailescu, 1991; Panin, 2004; Giosan *et al.,* 2005; 2006; 2012). The development of the delta at the open coast started approximately 6000-5500 ^{14}C years ago (Giosan *et al.,* 2012). Existing studies mainly are focused on river-mouth morphodynamics and delta-plain area expansion (Giosan *et al.,* 2012). Channel developments within the delta during this period are less well studied and only known in association with major delta-lobe development.

The Danube was one of the main advance routes for Neolithic agriculture from the Fertile Crescent into Europe (Carroza, 2012; Giosan *et al.,* 2012). The delta was also part of the Roman Empire from early in the 1st century AD to the last decades of the 4th century (Wilkes, 2005). In addition to the legionary fortress *Troesmis* (along the Lower Danube near modern Mâcin), there may have been as many as 18 auxiliary forts between Silistra and the mouth of the southern channel of the delta, St. George (Wilkes, 2005). The Roman fortifications along the Lower Danube were built at strategic locations situated directly along the river, which is at the few locations where the Danube river could be crossed (Alexandrescu and Gugl, 2016: *Arrubium, Dinogetia* and *Noviodunum*). Although Giosan *et al.* (2012) have demonstrated that 40% of the delta plain area was formed during the last two millennia as a consequence of upstream deforestation, for the Roman period detailed palaeogeographical reconstructions, especially of the upper delta river system are lacking (Carroza, 2012). The history of the deltaic system has yet to be clearly and convincingly uncovered (Giosan *et al.,* 2006; Romanesco *et al.,* 2015). No information is available on Roman settlement in the Danube delta itself and it is assumed that the invariably murky deltaic area was inhospitable for sustained human settlement. Conversely, the adjacent continental shelf favoured the establishment of human settlements during ancient and medieval times (Romanesco, 2013; Romanesco *et al.,* 2015).

Rhône delta

The large-scale palaeogeographical changes in the Rhône deltaic plain during the last 10,000 years are characterised by alternating periods of deltaic pro- and retrogradation (Arnaud-Fassetta and Landuré, 2003; Arnaud-Fassetta *et al.,* 2010). For every phase the distribution of three types of palaeo-environments (marsh, flood basin, natural levee) and coastal fringe have been reconstructed based on a dozen of corings. One of the most important causes of lateral channel instability in the Rhône delta is avulsion (Arnaud-Fassetta, 2004; Arnaud-Fassetta *et al.,* 2005). Previous sedimentary research in this delta mainly focused on the effects of catastrophic floods on delta development (Arnaud-Fassetta and Landuré, 2003; Arnaud-Fassetta *et al.,* 2005; 2010; Bruneton *et al.,* 2001). Four periods of increased fluvial activity with higher intensity of floods have been identified, occurring during the Middle Bronze Age, the Roman Period, Late Antiquity, and in post-medieval times (Little Ice Age). Detailed palaeogeographical reconstructions are only available on a local scale.

Archaeological evidence indicates remains of human activity dating from the Neolithic period and most sites were situated along the Rhône palaeochannels (Arnaud-Fassetta and Landuré, 2003; Arnaud-Fassetta *et al.,* 2010). The interrelationship between river behaviour and human settlement in this delta in general is mainly examined by the effects of catastrophic floods. These studies show that the majority of the sites (79%) was located along the active channels of the Rhône river, e.g. in the proximal flood plain, during the Roman antiquity and the Middle Ages and in general persisted in spite of recurrent floods, or contracted for reasons other than fluvial risk (Bruneton *et al.,* 2001; Arnaud-Fassetta *et al.,* 2010). Yet, when a site was subjected to hydrological disasters – e.g. when all physical hydrological risk factors were combined – it was abandoned.

Ebro delta

The Ebro delta located along the Spanish Mediterranean coast is the third largest delta in the Mediterranean, following those of the Nile and Rhône. Geological studies of the Ebro Delta and its Holocene sedimentary archives and evolution are scarce and most of them are supported by just a few radiocarbon dates (Cearreta *et al.,* 2016). The architectural stacking patterns of the depositional units of the Ebro delta show that the deltaic coast was intensively reshaped during the Holocene (Somoza *et al.,* 1997). The evolution of the delta is characterised by avulsions in the course of the main river channel, which in turn caused the development of successive delta lobes, later abandoned and partially eroded (Benito *et al.,* 2016). Periods of decreased sediment supply favoured channel switching on the delta plain causing rapid abandonment of the main delta lobes (Somoza *et al.,* 1998). The sequence of progradational deltaic lobe pulses, which occurred between resp. 6150 to 5350 yrs BP, 4400 to 3600 yrs BP, 2910 to 2700 yrs BP, AD 1100 to1300, and AD 1350 to1700, was distorted progressively by deltaic regression phases. The last regressive pulse occurred around AD 1750.

Hydrological simulations support the hypothesis that humans have contributed to the progradation of the Ebro delta over the last 4,000 years (Maselli and Trincardi, 2013). Human activities in this period, represented as land-use changes (as expressed by changing vegetation cover), had minor impact on water discharge (Xi *et al.*, 2014), but were the dominant control of suspended sediment load variations in the river by increasing hillslope sediment yield due to soil erosion after deforestation. Amposta, a town now located at the inland margin of the delta, had a marine harbour during Roman times (Cearreta *et al.,* 2016). This implies that since then, successive delta-lobe progradation has occurred, but detailed palaeogeographical reconstructions for this area per time period are still lacking.

Po delta

The Po delta and Venetian-Frulian Plain are the largest alluvial basins south of the Alps. The evolution of the Po delta system during the last few thousands of years was characterised by a general seaward migration of the coastline since the mid-Holocene (Correggiari *et al.,* 2005; Stefani and Vincenzi, 2005; Amorosi *et al.,* 2008a; 2008b; Carton *et al.,* 2009; Simeoni and Corbau, 2009). The alluvial plain behind the southern Venice Lagoon is characterised by a complex network of alluvial ridges formed by the aggradation of channel deposits and natural levees of the Adige and Po rivers (Amorosi *et al.,* 2008a; Piovan *et al.,* 2010; 2012). Major avulsive events in the upstream tracts of these rivers controlled the migration of delta lobes. The Venetian-Frulian Plain comprises the alluvial systems of the Brenta, Piave, and Tagliamento rivers forming alluvial megafans. Widespread aggradation of the lower sectors of these fans to the north started around 4-3 ka BP (e.g. Fontana *et al.,* 2008; Rossato *et al.,* 2015). Floodings played a major role in the Late Holocene evolution of the alluvial system (Arnaud-Fassetta *et al.,* 2003; Mozzi *et al.,* 2003; Fontana, 2006).

Anthropogenic impacts on the landscape grew in importance after the Neolithic period (Marchetti *et al.*, 2001; Piovan *et al.*, 2012). Detailed geoarchaeological and palaeo-environmental investigations (Piovan *et al.*, 2010; Mozzi *et al.*, 2010) have demonstrated that the changes in the hydrographical framework influenced the rivers' function as a transport route, thereby affecting both local and long-distance transalpine cultural connections. During the Roman Period almost complete deforestation occurred in the upstream basins, causing enhanced soil erosion and a maximum progradation rate of the Po delta (Marchetti, 2002). However, the Piave river was stable during this period and carried less water (Carton *et al.*, 2009). In the Isonzo delta, the shifting of rivers during Antiquity had an impact on the functioning of the large harbour of the Roman city *Aquileia*. However, this city continued to develop, in spite of recurring floods, because of its political importance (Arnaud-Fassetta *et al.*, 2003; 2010).

Rhine-Meuse delta

The Rhine-Meuse delta in the Netherlands is the most northern delta formerly incorporated into the Roman Empire. The evolution of this delta is well known from the Late Glacial onwards (Berendsen and Stouthamer, 2000; 2001; Cohen *et al.,* 2012). Palaeogeographical reconstructions of the delta and its active channel belts are available per 500-yr time step and exceptionally detailed. These reconstructions show the timing and location of avulsions, and provide a detailed overview of the active channel belts during the Roman period. Extensive peat formation occurred in the western part of the delta during the Roman period (Gouw, 2007; Gouw and Erkens; 2007), while in the proximal part of the delta clay deposition occurred (Stouthamer, 2001; Gouw and Erkens, 2007) which was the product of intensified human impact in the upstream catchment through intensified forest clearing and agricultural land use (Erkens *et al.,* 2011).

The Rhine delta served as a river frontier of the Roman Empire, the so-called *Limes*, from the earliest beginning in the last decades BC until the mid- 5th century, when the Western Empire collapsed (e.g. Van Es, 1981; Willems, 1986; Bechert and Willems, 1995; Polak and De Bruin, 2016). An array of forts was built along the southern bank of the Rhine to the North Sea coast. The location and dating of most forts is well-known, and many forts have been (partly) excavated (e.g. Glasbergen, 1972; Glasbergen and Groenman-van Waateringe, 1974; Haalebos, 1977; 1995; Kalee and Isings, 1984; Willems, 1986b; Ozinga *et al.,* 1989; Van Enckevort *et al.,* 2000; Van Enckevort and

Thijssen, 2003; Polak *et al.,* 2004; Blom and Vos, 2008; Zandstra and Polak, 2012; Vos *et al.,* 2016). The earliest fortification, the legionary fort at Nijmegen, was erected in 19/16 BC (Driessen, 2007; Kemmers, 2006). Only from the beginning of the 1st century AD, smaller bases were erected further westward and the Lower Rhine river became the northwestern frontier of the Empire, the *Limes*, and of the Roman province of *Germania Inferior* from the second part of the 1st century onwards (Polak, 2009). On the higher alluvial ridges rural settlements occurred throughout the entire delta (Willems, 1986a; Vossen, 2003; Van Londen, 2006; Vos, 2009). During the Late Middle Ages, large-scale land reclamation began, involving drainage of flood basins and subsequent heightening of embankments in order to to protect the reclaimed areas from flooding. Around AD 1350 all active river branches in the Rhine-Meuse delta were embanked, preventing flooding of the former floodplains as well as new river avulsions.

In conclusion, the Rhine-Meuse delta was the only delta in the Roman Empire that continuously was a part of the Roman frontier, the *Limes*, containing military installations from all successive phases of Roman military strategy, e.g. conquest, forward defence and defence-in-depth (Polak and de Bruin, 2016). The specific environmental situation characterized by constantly changing and bifurcating river channels generated constructive challenges and demanded for reactive strategies specially adapted to this dynamic environment. The Danube delta temporarily was a part of the Roman frontier, but for this area hardly any (geo)archaeological data and detailed palaeogeographical reconstructions are available. Therefore, this thesis mostly focuses on the fluvial archives and embedded archaeological records of the Rhine-Meuse delta. The Oude Rijn tributary in the western segment of this delta was a part of the *Limes* for a prolonged period. The fluvial archive and archaeological remains of this distributary are exceptionally well preserved, since later river erosion was limited and subsequent overbuilding and deep-soil disturbances were relatively restricted.

1.3 Problem description

The overview presented above clearly shows that the evolution of the deltas of the Roman Empire was characterized by phases of expansion, due to an increased sediment yield from the upstream basins. At the same time, major avulsions occurred and different delta lobes formed. Within these active fluvial and delta regions, small rural settlements had developed, which were complemented by Roman cities and by forts of the Empire.

However, the existing knowledge merely tells us that at this time societies lived in dynamic fluvial and delta regions and the available data from these deltas is insufficient to reconstruct how the natural landscape functioned, how it affected these societies, and how societies responded to environmental changes. Existing reconstructions of deltas indeed indicate the location of the active delta lobes and distributaries, but do neither provide detailed landscape reconstructions at delta or regional scale, nor show information on the human-landscape interaction. Even in the Rhine-Meuse delta with its detailed database of meander belt generations, landscape reconstructions of the adjacent natural levees, flood basins, and crevasse systems are lacking. In turn, the numerous archaeological excavations in the Rhine-Meuse delta have been analysed mostly in a local context, while an analysis of settlement locations and land use at river-reach scales remains to be done. Understanding the consequences of landscape changes for prehistoric and Roman settlement and human use requires the challenging exercise of reconstructing the past delta landscape and its dynamics, integrating large numbers of local archaeological site data to a regional scale, and relating these to the supporting landscape. This exercise also requires integration of disciplines, since it involves the combination of natural sciences approaches resulting in reconstructions of the natural environment with humanities-based approaches resulting in reconstructions of the socio-cultural human past. Because of the enormous amounts of available geological and archaeological data, the Rhine-Meuse delta may provide the best opportunity in comparision to other deltas for the cross-disciplinary challenge to take the next step forward in understanding delta-landscape dynamics and their influence on past settlement and land use.

1.4 Previous research in the Rhine-Meuse delta

Although alluvial landscapes have been the subject of geo-archaeological research worldwide, and in spite of the growing number of studies employing archaeological evidence in combination with radiocarbon and OSL-dating, modern surveying techniques, and GIS-methods, with the aim to reconstruct Holocene river histories, there have been few attempts to synthesise these data at delta scale. In the temperate setting of the Rhine-Meuse delta both delta evolution and its archaeological history are exceptionally-well studied. Consequently, combined studies of fluvial archives and (geo) archaeology at delta scale so far only have been conducted in the Rhine-Meuse delta. Therefore, the Netherlands play a leading role in this kind of cross-disciplinary research and this helps to gain better time control on river development and better understanding of human settling along rivers.

In the Netherlands, the geological and archaeological disciplines have developed a long-standing research tradition regarding the river delta and in addition for this region have established a long-lasting relationship in terms of collaboration and exchange. Already since the middle of the 20th century an integrative approach of geological/soil analysis and archaeological research was promoted by the Dutch Soil Survey (in Dutch: Stichting voor Bodemkartering (Stiboka)) and the Dutch Cultural Heritage Agency (Rijksdienst voor het Oudheidkundig Bodemonderzoek – ROB, later renamed into RCE). At this time geological and soil studies mainly were performed based on comprehensive coring campaigns. However, during this process soil layers containing archaeological finds and phosphate staining also were described in detail, contributing to the establishment of more detailed geological chronologies. This resulted in a series of interdisciplinary publications revealing the relationships between e.g. landscape and habitation patterns (e.g. Modderman, 1949a; 1949b; 1955; Edelman, 1950; Pons and Modderman, 1951; Louwe Kooijmans, 1974; 1985; Havinga and Op 't Hof, 1975; 1983; Henderikx, 1987; Havinga, 1989; 1993). As a result, we now have collected an amount of geological and archaeological data in the Rhine-Meuse Delta that is unequalled worldwide. Additional coring campaigns, mainly by the department of Physical Geography at Utrecht University and the Geological Survey of the Netherlands, have resulted in >30 corings/ km^2 in the delta, which are available through a national digital database (www.dinoloket.nl), and in detailed palaeogeographical reconstructions of the entire delta, available through a database comprising over a thousand radio carbon dates chronologically dating fluvial units (Berendsen and Stouthamer, 2001; Berendsen and Stouthamer, 2006; Cohen *et al.*, 2012).

The archaeological history of the delta is well known, although many sites have remained unexcavated. The number of observations has boomed especially after contract archaeology started in the 1990s. The Dutch archaeological domain changed even more profoundly when the Council of Europe drew up the Valetta Treaty (European Convention on the Protection of the Archaeological Heritage) in 1992. This treaty aims to protect the European archaeological heritage '*as a source of European collective memory and as an instrument for historical and scientific study*' (https://rm.coe.

int/CoERMPublicCommonSearchServices/DisplayDCTMContent?documentId=090000168007 bd25) and implies that archaeological investigations have to take place before any disturbance of the subsoil occurs, e.g. as the result of building activities. Nationally as well as internationally this has further stimulated the development of a commercial archaeological sector. In the Netherlands this development has coincided with the organization of archaeological quality-control mechanisms and tools at a national level, such as national digital repositories and requirements of the storage of digital research materials and results. At present >15,000 archaeological observations pertaining to the Rhine-Meuse delta have been archived in the national Heritage Monitor Database (De Boer *et al.*, 2009; https://erfgoed.databank.nl/) and many archaeological prospective and excavation reports are publical available through the national archaeological repository DANS Easy (https://easy.dans.knaw.nl). In addition, a variety of databases have been developed at lower organizational levels in the Netherlands (e.g. municipality level). Altogether, these databases allow synthesising and reviewing local archaeological studies, and analysing the effect of the landscape on settlement locations in the delta over various time periods (e.g. Arnoldussen, 2008; Heeren, 2009; Vos, 2009; Dijkstra, 2011). However, in published studies detailed palaeogeographical reconstructions of the landscape around the sites as well as large-scale palaeogeographical reconstructions are mostly lacking.

Archaeological sites in the Rhine-Meuse delta are characterised by high ground-water levels resulting in a low-oxygen environment, and are therefore renowned for their excellent preservation of fragile organic remains, such as seeds, pollen, wood (timber, small utensils, vessels, etc.), bones, and leather. Because of their rich organic content these sites provide more environmental information and evidence of landscape use than sites at better-drained locations (e.g. the sandy soil in the eastern Netherlands). In addition, the excellent preservation of organic material in this area has enabled the application of ^{14}C-dating on a large scale, resulting in a detailed chronology of both the fluvial systems and the archaeological archive. This facilitates the search for patterns in the interaction between humans and their environment and the assessment of the effect of environmental change on human land use (Fig. 1.1).

The wealth of geological and archaeological data, stored in accessible databases and representing the excellent preservation conditions in the Rhine-Meuse delta (www.dinoloket.nl), constitute a perfect case to provide detailed palaeogeographical reconstructions of the complete Oude Rijn tributary, a *Limes*-section, and to decipher the effect of the landscape and its dynamics on settlement locations in the delta in various time periods on a larger geographical scale. Combining knowledge from the geosciences and archaeology provides a unique insight into the complex relationships between environmental change and human land-use behaviour through time.

1.5 General objective and research questions

The main objective of this study was to assess the impact of environmental change on human activity along the Oude Rijn in the Roman and Early Medieval periods (~AD 1-1122). This was mainly achieved by spatial analysis and integration of existing geological and archaeological data from this dynamic river landscape, where necessary complemented with newly acquired data. This study thereby aims to enhance our generic understanding of past river environments and their influence on human settlement and land use.

Six specific research questions follow from this main objective:
1. How did the landscape along the Oude Rijn look in detail in the Roman and Medieval periods?
2. Which landscape elements were used for settlement locations?
3. To what extent and how was the outline of the northwestern frontier of the Roman Empire – the *Limes* – determined by the natural landscape of the Rhine delta?
4. To what extent could the natural landscape of the Oude Rijn provide the local population and the Roman army with sufficient supply of wood and food?
5. How did the evolution of the Oude Rijn distributary effect occupation patterns?
6. What was the interrelationship between the landscape development and settlement change, and to what extent did the landscape and environmental change constrain human activities?

1.6 Approach

To answer the research questions a two-step approach was deployed (Fig. 1.3). During step 1, a landscape analysis was conducted for the Oude Rijn area using a Geographical Information System (GIS). Various maps with geoscientific information covering (parts of) the Rhine-Meuse delta are available, including geological, geomorphological and soil maps (scale 1:50,000; locally scale 1:10,000), which formed the starting point of the development of detailed palaeogeographical reconstructions. These maps were improved and adapted by adding information from coring datasets (www.dinoloket.nl) and local municipality databases, and (older) topographical maps. In addition, a county-wide LIDAR elevation dataset with excellent resolution has recently become publical accessible (Rijkswaterstaat-AGI, 2005; www.AHN.nl). Furthermore, a considerable number of reports on (geo)archaeological research conducted in the Rhine-Meuse delta has become digitally available during the last decades mainly through DANS Easy. By combining these site-scale data,

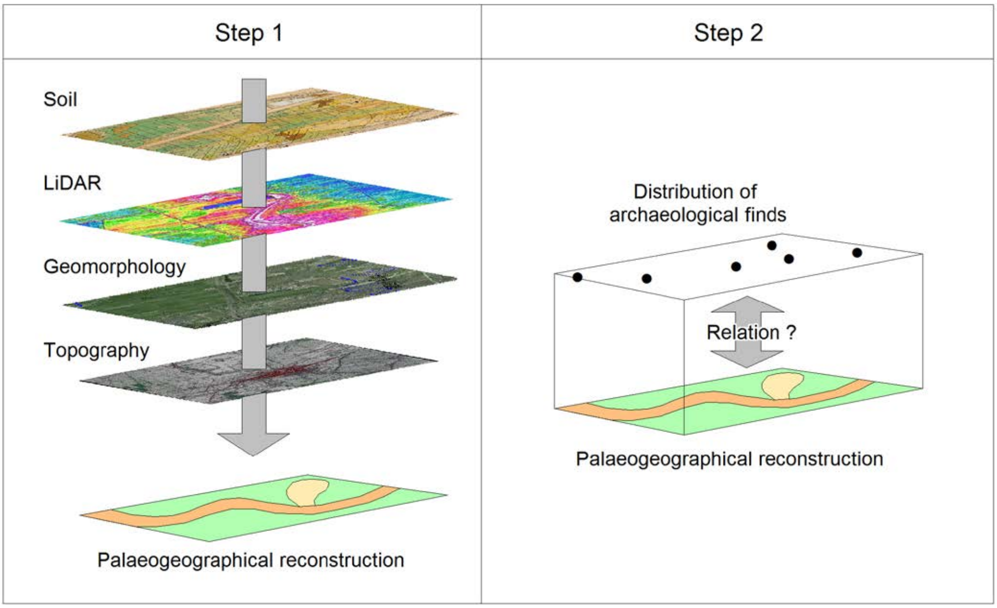

Figure 1.3 Schematic overview of stepwise research approach.

regional-scale reconstructions of settlement patterns and palaeogeographical reconstructions were made. Information about the various archaeological sites in the research area was retrieved from the Archaeological Information System of the Netherlands (https://archis.cultureelerfgoed.nl) and from archaeological prospective and excavation reports and local municipality databases.

Step 2 entailed the overlaying of resulting archaeological site distributions on palaeo-geographical maps (Fig. 1.3). This enabled identifying spatial relationships between settlement location/land use and geomorphological units. Furthermore, it was analysed whether changes of settlement locations coincided with landscape changes, and thus might be triggered by landscape development through time.

These steps were first undertaken to reconstruct the landscape of the Oude Rijn, the *Limes*, during the Roman period. This resulted in a map of the landscape at that time, together with the position of the identified Roman military installations, which revealed the strategic relevance of the landscape for the location of these installations. The results answer research questions 1 and 3 (Chapter 2).

Additionally, the formation and landscape of crevasse splays was analysed to understand the attractiveness of these often short-lived landscape features for human settlement and use in general. The results show how environmental changes dictated human activities, and answer in part research questions 2 and 6 (Chapter 3).

An extensive review was made of the data on agrarian settlements, to determine whether the landscape of the Oude Rijn provided wood and land for cattle grazing and cereal production, and thus whether it could supply the local inhabitants and Roman army with sufficient building material, fuel, and food. The palaeogeographic landscape reconstruction was used as a template for the surface area needed for wood and food production, and a quantitative model was established to enable the comparison of the potential supply from the landscape to the demands of the population. The results answer questions 2 and 4 and are presented in Chapters 4 (qualitive reconstruction of landscape, population and their food and wood production and consumption) and 5 (quantitative estimates of supply versus needs).

Focusing on the whole of the first millennium AD, a detailed reconstruction was made of the channel course of the Oude Rijn during its long-term abandonment, and its effect on human occupation in the area was assessed. The Oude Rijn was the main Rhine artery for thousands of years, and thus formed an ideal research case to study the interrelationship between landscape development and settlement change. The results show which constraints of the landscape and environmental change affected human activities, answering questions 5 and 6 (Chapter 3).

The main conclusions of this thesis are presented in Chapter 7, outlining the added value of interdisciplinary studies which give a unique insight into the complex relationships between environmental change and human behaviour in an unembanked river delta over longer and shorter periods of time. In addition, possible directions for future research are outlined in this chapter.

1.7 Research framework

The research underlying this thesis was part of several research projects. The presented reconstructions of the *Limes* landscape and the analysis of the landscape provisioning (presented in Chapters 2 and 4-6) was part of the project '*A sustainable frontier? The establishment of the Roman frontier in the Rhine delta*' (application number VOM-02-04/OM-03-05; applicant: Prof. dr. M. Erdrich, Nijmegen University). This interdisciplinary project focused on the interaction between

potential supply provided by the landscape and military requirements during the 1st and early 2nd centuries AD (AD 40-140).

The reconstructions of the settlements in the Utrecht area and their relationship to the gradual avulsion of the Oude Rijn branch (presented in Chapter 6) were part of a research project of Utrecht University entitled '*Treasures of the Dom square; reconstructing Roman and Early-Medieval Utrecht: new approaches*'. Within this project the faculties of Humanities and Geosciences collaborated in archaeological, historical, and geo-scientific research of the history of the present Dom Square in Utrecht in a wider geographical and cultural context, focusing on the first millennium AD.

As this thesis consists of five journal papers which were recently published, some repetition may occur in the description of the study areas and their geological and archaeological setting.

2 The Roman *Limes* in The Netherlands: how a delta landscape determined the location of the military structures

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2.1 Introduction

During the first centuries AD, the Roman army established a linear frontier system in the Rhine-Meuse delta in the Netherlands (Van Es, 1981; Willems, 1981; Bechert and Willems, 1995). By the middle of the 1st century AD a series of small auxiliary forts was built in the western part of this delta from the present-day city of Utrecht down to the North Sea over a distance of about 60 kilometres (Bosman and De Weerd, 2004; Polak *et al.,* 2004; Polak, 2009). The fortifications were constructed on the left bank of the Lower Rhine and built exceptionally close together compared to the upstream part of the delta and Germany (Fig. 2.1).

During the Holocene, the Rhine-Meuse delta consists of a varying landscape formed by the interaction of fluvial and marine processes. The downstream part of the delta was relatively starved of both fluvial and tidal sediments (Erkens *et al.,* 2006), the distance to other Rhine distributaries was large, while the distal parts of the flood basins were isolated from influence of active river channels. This situation favoured peat formation (Gouw, 2007). This caused extensive peat formation in this part of the delta during the Roman period which resulted in a landscape that has been considered previously as a hardly accessible and marginal landscape (Van Es, 1981; Bloemers, 1983; Whittaker, 1994). Hence, the question arises why such a closely spaced linear defence system was established here at all and in the course of time even turned into the northwest frontier of the Roman Empire, the *Limes*.

While providing constricted conditions for settlement in Roman age, the preservation conditions of artefacts, especially ecological material, have been exceptionally high due to the high water levels in this wetland area. Furthermore, the Roman military structures along the Lower Rhine are well preserved in subsurface, because hardly any post-Roman river erosion occurred in contrast to the central and eastern part of the delta (Bechert and Willems, 1995). Hence, it is an ideal study area for both archaeological and geological research into this reach of the Roman *Limes*.

Archaeological research into the military history of the Roman frontier zone was traditionally almost exclusively focused on the size and lay-out of the individual forts and their building history (e.g. Van Giffen and Glasbergen, 1947; Van Giffen, 1948; 1955; Van der Klei, 1970; Glasbergen, 1972; Haalebos, 1977; Bogaers and Haalebos, 1983; Kalee and Isings, 1984; Ozinga *et al.,* 1989; Polak and Wynia, 1991; Van der Gauw and van Londen, 1992). Usually, little attention was given to the reconstruction of the surrounding landscape. Only during extensive archaeological excavations near Valkenburg (Fig. 2.1) thorough geological research was carried out (Van Dierendonck *et al.,* 1993). This research showed that the human occupation here occurred in a very dynamic environment.

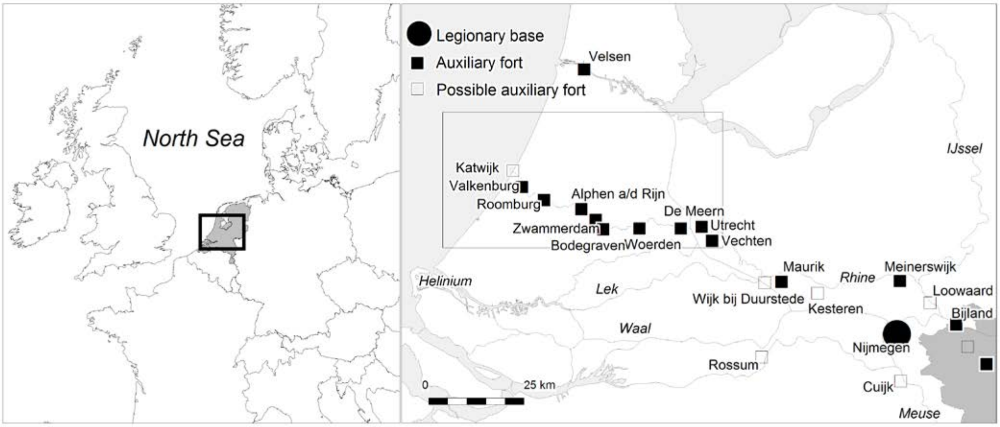


Figure 2.1 Roman fortifications in the Rhine-Meuse delta, the Netherlands, in the first two centuries AD, projected on modern topography (after Polak, 2009). Box indicates the research area.

Since then, geological and environmental investigations became an essential part of the many archaeological excavations in the former *Limes*-zone. These investigations provided considerable information about the landscape and its development during the first centuries AD and showed that the Romans had to adapt to the specific problems and restrictions nature imposed (e.g. Berendsen and Wynia, 1993; Vos and Lanzing, 2000; Vos and Blom, 2003; Polak *et al.*, 2004; Van der Kamp, 2009).

However, the results of these studies have not been integrated into a larger framework. Therefore, a detailed insight and understanding of the interactions between the natural environment in the Rhine river delta on the one hand and the establishment and maintenance of this section of the *Limes* on the other is lacking. The objective of the study reported here is to assess the influence of the landscape on the location and size of the military structures erected in the western *Limes*-section in the first two centuries AD based on available geoarchaeological data (Fig. 2.1). This chapter first presents a new and detailed reconstruction of the palaeo-landscape in this part of the *Limes*-zone in the Roman period. The processes active in this landscape at different scales and the resulting development of the environment are described. In addition, the location of all military structures in this landscape is outlined. Finally, the influence of the landscape on the position and lay-out of the various military elements in the research area is revealed. In this way, this chapter contributes to a better understanding of the reasons why the Roman army settled along a river branch in an unembanked delta plain.

2.2 The study area

Geological setting

During the Roman time period, wide-spread peat formation occurred in the Netherlands. Therefore, extensive areas were almost inaccessible and habitation was limited. The apex of the delta was located near the German border (Gouw and Erkens, 2007). The delta was bordered by topographically higher Pleistocene deposits in the north and south and the coastal dunes in the west. The current research area is situated in the northwestern part of the Rhine-Meuse delta (Fig. 2.2).

Alluvial ridges and flood basins formed the major geomorphological features with only slight height differences of less than one to two meters. The alluvial ridges consist of natural levees, completely or partly silted up swales and residual channels, and point bars (Cohen et., 2009). The elevated levees were gradually formed during annual floods, when the rivers deposited overbank sediment along their channel. In the low-lying flood basins farther away from the river clay was deposited during overbank flooding. Furthermore, small channels could erode through the natural

Figure 2.2 Palaeogeographic map of the Netherlands in 1st century AD Box indicates the research area. Map is based on several studies (Westerhoff et al., 2003; De Bont, 2008; Van Beek, 2009; Cohen et al., 2009; Vos et al., 2011).

levees during peak discharges, resulting in the deposition of coarser sediment in the flood basin, referred to as crevasse splay deposits (Smith, 1983; Berendsen, 2004).

During the Roman period, a network of coexisting Rhine and Meuse distributaries was active within the delta. The distribution of active channel belts in the first centuries AD is shown in Fig. 2.3. The river branch along which the chain of Roman auxiliary forts was built formed the second largest river mouth of the Rhine-Meuse delta and is nowadays referred to as Oude Rijn (Berendsen and Stouthamer, 2001) or '*R(h)enus*' by the Romans (Tacitus, *Annales* II,6). In Utrecht, the Vecht bifurcated from the Rhine. This branch, referred to as '*Flevum*' by Plinius, discharged into the North Sea near Castricum, but was most likely also connected to Lake Flevo (Plinius, *Naturalis Historia* IV, 101; Fig. 2.2). By the middle of the 1st century AD, the estuary near Castricum had silted up (Bosman, 1997; Vos, 2008). Thereafter, all Vecht water discharge was diverted to lake Flevo and in turn to tidal flats in the North (Fig. 2.2; Plinius, *Naturalis Historia* XVI, 2-3). The southernmost river mouth of the combined Waal and Meuse rivers was the largest outlet to the North Sea and called *Helinium*' or described as *Os Immensum*' (enourmous outlet) by the Romans (Plinius, *Naturalis Historia* IV, 101; Tacitus, *Annales* II,6; Fig. 2.2). Yet, the channel system in the delta was a continuously changing network. The actual position of the river channels altered in time through lateral migration, meander cut-offs and avulsions (Berendsen and Stouthamer, 2001).

The water discharge of the Oude Rijn gradually decreased during the Roman period. This was caused by a steadily redirection of the water flux in the Nederrijn towards the more southerly Hollandsche IJssel distributary and later on to the Lek (Fig. 2.3). Because of this development, the fluvial activity of the river Vecht also reduced, ultimately resulting in the onset of peat growth on

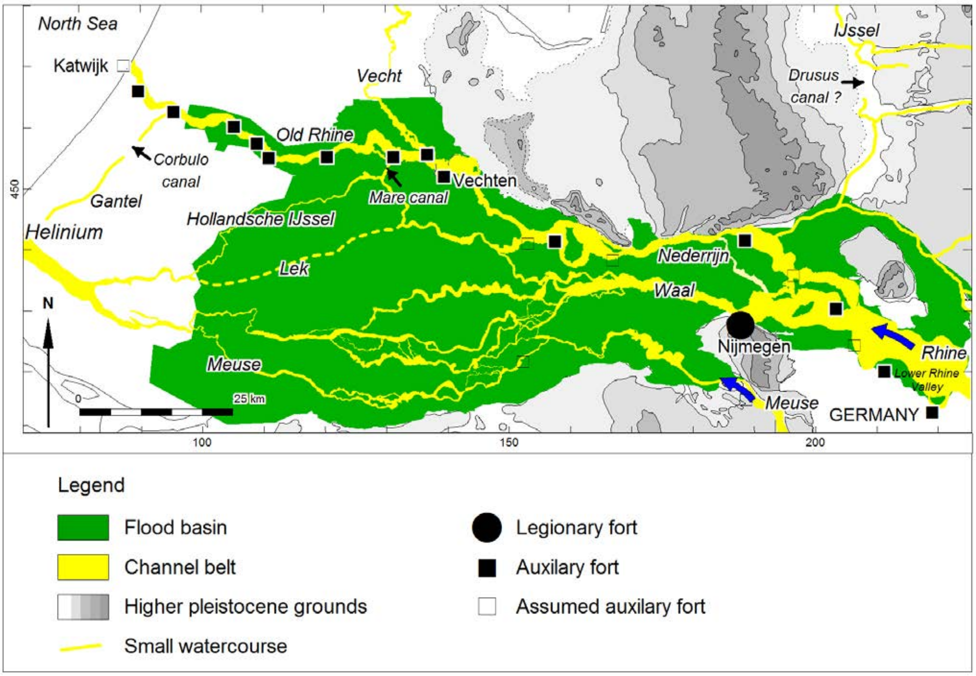


Figure 2.3 Active channels belt in the Rhine-Meuse delta in the first two centuries AD (modified after Erkens and Cohen, 2009).

the lower parts of the natural levees from the end of the 3rd or early 4th century AD onwards (Weerts, Cleveringa and Gouw, 2002).

Despite the reduction of the water discharge in the Oude Rijn, the flood frequency and magnitude of the floods probably increased along the Oude Rijn during the Roman period, concurrent with the general trend in the Rhine-Meuse delta during this time period (e.g. Kwadijk, 1993; Berendsen and Stouthamer, 2001; De Moor, 2007; Gouw and Erkens, 2007). This increase is attributed to increased human impact in the upstream catchments of Rhine and Meuse through intensified forest clearing and agricultural land use. This also resulted in considerable increases in sediment supply and overbank sedimentation (Erkens *et al.,* 2011). Because of large- scale clastic sedimentation peat formation in the flood basins ceased in the eastern part of the Rhine-Meuse delta (Stouthamer, 2001; Gouw and Erkens, 2007). Furthermore, it triggered vertical channel aggradation instead of incision in the Lower Rhine Valley in Germany just upstream of the Rhine delta (Erkens *et al.,* 2011).

Roman occupation

Roman occupation of the Rhine-Meuse delta started during the Augustian military campaigns with the building of a large legionary base in Nijmegen between 19-16 BC (Driessen, 2007). Soon, in 12 BC, this camp was abandoned (Kemmers, 2006). Only in the early part of the 1st century AD, a sequence of smaller military bases were erected further to the west along the Rhine: a fort at Vechten, at Meinerswijk and at Velsen (Willems, 1984; Morel, 1988; Polak and Wynia, 1991; Bosman, 1997; Bosman and De Weerd, 2004; Polak, 2006). From AD 40s onward a number of new auxiliary forts was established on the left bank of the Oude Rijn downstream of Vechten. Together they formed a chain of ten forts built exceptionally close together (Fig. 2.1).

Until recently, it was generally thought that Valkenburg was built in AD 39/40 by Caligulan troops, while the others were only erected in or shortly after AD 47, the year that general Corbulo was ordered to withdraw his troops to the left bank of the river Rhine by emperor Claudius (Polak, 2009; Tacitus, *Annales* XI,19). However, recent excavations have radically changed this theory as founding dates around 40 AD are established for Valkenburg, Alphen aan de Rijn, De Meern and supposedly also for Woerden (Kemmers, 2008). This implies that the birth of the Lower Rhine *Limes* took place during the reign of Caligula instead of Claudius' (Polak, 2009). Occupation of most forts along the Oude Rijn and their associated settlements, the *vici*, is generally assumed to end in the 3rd century AD (Van Es, 1981; Kemmers, 2008).

All fortifications in the research area were initially constructed out of timber and earth, had a rectangular plan form and covered roughly one to two ha. Thereby, the forts are relatively small compared to fortifications upstream along the river Rhine. Furthermore, they differ in lay-out with only two strips with buildings in stead of three. The small size of the forts is generally attributed to limited width of the natural levees (Hessing, 1995).

2.3 Methods and materials

Palaeogeography

Although a general overview exists of the landscape of the Rhine-Meuse delta in the Netherlands (Fig. 2.2) understanding of the position of the fortifications requires a much more detailed reconstruction of the environmental settings of the military structures. To reconstruct the landscape of the first centuries AD, a detailed palaeogeographical map of the study area was created using a Geographical Information System (GIS; Fig. 2.4 and Appendix A, available online). Soil maps, geological and geomorphological maps, scale 1:50,000, formed the starting-point for this reconstruction (Appendix B, available online). These maps show the composition of the subsoil, the origin of the landforms and the age of formation, and together provide a good overview of the palaeogeography of the study area. All maps were geo-referenced in the Netherlands Coordinate System – Netherlands National System. Following this, these maps were adapted and improved by using a high-resolution digital elevation model (DEM) of the present land surface based on laser altimetry (LIDAR; Rijkswaterstaat-AGI, 2005). This dataset allowed to add more spatial detail to the maps and to provide a greater accuracy, as well as to map patterns and features that were invisible in the field and/or missed in earlier mapping campaigns (Berendsen and Volleberg, 2007; De Boer *et al.,* 2008).

The DEM was created from the original laser data points by means of inverse squared distance weighting, resulting in a 5 x 5m elevation grid used in this study. The general downstream gradient of the terrain surface was determined by plotting the highest altitudes of the river levees versus the horizontal-coordinate (Berendsen, 1982). The original elevation models were corrected for this general terrain gradient by subtracting this gradient surface from the original model. In this way, an elevation model was obtained indicating the local terrain elevation relative to the general terrain slope, at 10 cm height intervals to allow detection of the small elevation differences (Berendsen, 2007). By overlaying this relative DEM over the existing maps, it was possible to correct and refine the mapping in the present-day agricultural areas (Berendsen and Volleberg, 2007). In urban areas, borehole data, archived in the DINO-database of TNO – Geological Survey of the Netherlands were used to retrieve information on composition of the subsoil and thereby the palaeogeographical situation in former times.

Because micro topographical differences determined local flooding frequency and ground water level, and accordingly the suitability of the area for human activities, the legend units 'natural levees' and 'flood basins' were subdivided into sub-classes according to their height, using elevation steps of about three dm (Appendix A). In most areas, the modern surface topography of the natural levees and flood basins does not reflect the palaeo surface topography due to later erosion and disturbance of the deposits. Firstly, post-Roman fluvial erosion and sedimentation occurred, but – fortunately – lateral river migration of the river Rhine in the research area occurred only to a small extent (Bult *et al.,* 1990; Nokkert *et al.,* 2009). From the medieval period onwards large-scale excavation of clay or sand occurred by humans as raw material for e.g. bricks, roads and dikes to a depth of one to two meters in the natural levees of the Rhine, resulting in low-lying excavated plots, often with steep edges.

Furthermore, the micro topographical differences in the past were presumably smaller due to subsidence by peat compaction caused by artificial lowering of groundwater tables during the last centuries (Van Asselen *et al.,* 2009). This subsidence not only occurred in the peat area and flood basins, but also along the margins of the alluvial ridges where the natural levee deposits lie on top of older flood basin and peat deposits. Field studies have shown that subsidence of several mm/yr occurred in the central part of former fen peat areas, leading to surface subsidence of at least one meter since land reclamation in the 11th century (Schothorst, 1977; Beuving and Van den Akker, 1996; Jansen *et al.,* 2007). The induced subsidence accordingly resulted in relief amplification of channel belts.

Crevasse splays were included in the unit 'natural levees', because the splay deposits formed relatively high areas extending from the distal parts of the levees and provided similar conditions for human land use (Chapter 3). Several excavations provided evidence that crevasse splays formed during the first centuries AD (Vos and Lanzing, 2000; Vos and Blom, 2003; Vos and Blom, 2004; Ploegaert, 2006; Den Hartog, 2009; Langeveld and Luksen-IJtsma, 2010). Unfortunately, we have no absolute age evidence on the formation of the majority of these splay complexes. In addition, the splays gradually lost their relatively high position in the landscape due to subsidence and ongoing sedimentation in the flood basins. Yet, archaeological finds dated to the Roman period are recorded on top of many splays revealing human land use in Roman times (Appendix A). Therefore, all splays that are visible in the DEM due to differential compaction were mapped in this study.

The reconstruction of the position of the river within its channel belt during the Roman period is based on a number of excavations that revealed the location and depth of the Roman river channel (Appendix B). Furthermore, the DEM shows elongated depressions in the alluvial ridge of the Oude Rijn suggesting the presence of swales and residual channels. Unfortunately, no ^{14}C-dates from these channels were available to give age control. The reconstruction of the river mouth, the estuary, is based on a detailed soil map of this area (Van der Meer, 1952). The spatial distribution of the salt marshes in the estuary is, however, not based on detailed field data, and has therefore been indicated in a more schematic way to give an impression of the former landscape.

Although different botanical types of peat must have been present in the wetlands of the river delta in former times, palaeogeographic maps usually do not distinguish between them (Van Es, 1981; Henderikx, 1983; Westerhoff *et al.,* 2003; Vos, 2006; Vos *et al.,* 2011; Bos *et al.,* 2009). The peat types in the palaeogeographical reconstruction are mainly based on the Soil maps of the Netherlands, scale 1:50,000, that distinguish the type of peat present in the subsoil (Figure 2.4). Due to large-scale peat digging for fuel from Medieval times onwards, nowadays only small remains of the former peat domes have been preserved in the Netherlands. Nevertheless, excavations in some of these remains confirmed the presence of *Sphagnum* and *Eriophorum* peat in the presumed peat domes in the research area (e.g. Roller, 2003; Bakels and Kuijper, 2007; De Kort and Raczynski-Henk, 2008). The spatial distribution of the oligotrophic peat domes and surrounding mesotrophic reed and sedge fields is roughly based on the contours of the modern polders, because they supposedly mark the boundaries of these types of peat that were the most useful to excavate for fuel purposes (Van Wallenburg, 1966; Pons, 1992).

The reconstructed lakes in the former peat domes are situated in areas that have the toponym '-lake' on historical topographic maps (in Dutch: '-meer'), indicating the presence of former lakes (Appendix B). Lakes are common phenomena in present-day peat domes. Unfortunately, we have no time control on the establishment of the lakes. Presumably, the lakes gradually expanded eastward in time, because of prevailing westerly winds (De Bont, 2008). Some of the 'lake'-areas, such as Braassemermeer, Haarlemmermeer and Zijdelmeer, formed the starting point of curved ditch patterns, indicating the presence of a former drainage network.

The distribution of the dunes is based on the geological map of the Netherlands, scale 1:50.000 (Van der Valk, 1995) and slightly modified on the basis of micro topography shown on the DEM. Yet, detailed coring campaigns and archaeological excavations have shown that their distribution is even more complex than appears from the map (Veenenbos and Van der Knaap, 1954; Rieffe, 2007; Rieffe, 2009).

After Roman times, sea-level rose by c. two meters and the coastline in the study area experienced progressive coastal erosion (Beets and Van der Spek, 2000; Vink *et al.,* 2007). As a result, the Roman coastal landscape has partly disappeared. The reconstruction of the Roman shoreline was therefore based on existing reconstructions (Beets *et al.,* 1992; Beets and Van der Spek, 2000; Van Heteren and Van der Spek, 2008).

Archaeology
The position and lay out of the Roman forts were based on Chorus (forthcoming), and the location of watchtowers and canals were obtained from archaeological excavations (Appendix B). Only field campaigns carried out before 2009 are included in this study. Locations where additional military complexes are postulated are indicated in grey. The course of the Roman road, *via militaris*, is mainly based on Luksen-IJtsma (2010). Furthermore, all Roman finds spots reported to the Dutch Cultural Heritage Agency and administered in the ARCHIS-database until January 2009 are shown (Appendix A). The depicted rural settlements are only partially based on actual excavations (Appendix B). The majority is inferred from the ARCHIS-reports with the method described by Vos (2009; Chapter 4).

2.4 Results

2.4.1 Palaeolandscape

The palaeogeographical situation in the study area in the first centuries AD is shown in Fig. 2.4. A more detailed map, scale 1: 50,000, is presented in Appendix A.

Natural levees
The alluvial ridge of the Oude Rijn formed a relatively narrow corridor of accessible terrain within a vast wetland. The natural levees consisted of sand and sandy clay and reached a maximum of one and a half meters above the surrounding flood basin. The alluvial ridge reached a maximum width of about two kilometres around Utrecht and a minimum of c. 800 meters between Bodegraven and Alphen aan de Rijn. Under natural conditions, natural levees in the Dutch fluvial area carried an alluvial hardwood forest characterized by a high species diversity with beech (*Fagus sylvatica*), hazel (*Corylus avellana*), lime (*Tilia cordata*), field maple (*Acer campestre*), oak (*Quercus robur*), elm (*Ulmus* sp.), ash (*Fraxinus excelsior*) and hornbeam (*Carpinus betulus*) (Fig. 2.5a; De Klerk *et al.,* 1997; Wolf *et al.,* 2001). Wood remains of the Roman fort in Alphen aan den Rijn reveal that the timber used between AD 40-70 was retrieved from such forests, probably located in the vicinity of the fort (Van Rijn, 2004; 2009; 2017). Around AD 70 these forests had almost completely vanished (Kooistra *et al.,* 2014; Van Rijn, 2017). The natural levees in the eastern and the western part of the research area were already largely deforested in the Early Roman period due to exploitation of the natural woodlands in the preceding Late Iron Age (Vos, 2009).

The width of the river channel of the Rhine in the Roman period varied within the research area. In the eastern part of the research area, between Vechten and Utrecht, the river channel was around 100 meters wide and 7 meters deep (Aarts, 2012; Jansen *et al.,* 2014). In this area, Pleistocene aeolian sand deposits are present only a few metres below the surface. This sand was easily erodible, causing rapid river migration and the formation of shoals. Downstream of Utrecht and the bifurcation of the river Vecht, the river channel seems to have been around 40 to 80 meters wide, around 4-6 meters deep and probably contained fewer sandbanks (Aarts, 2012). Between Alphen aan den Rijn and Leiden, the river probably had two channels that successively divided and merged over a length of around 15 kilometres. In between these channels, stable islands around one kilometre wide and two to three kilometres in length were present. Approximately two kilometres west of Valkenburg, the river graded into a funnel-shaped estuary with a mouth just over two and a half kilometres wide. As in all estuaries, tidal channels separated by sandbanks were present in the centre and flanked by muddy flats and salt marshes dominated by halophytic herbaceous plants (Fig. 2.5b; Reading and Collins, 2006, 216).

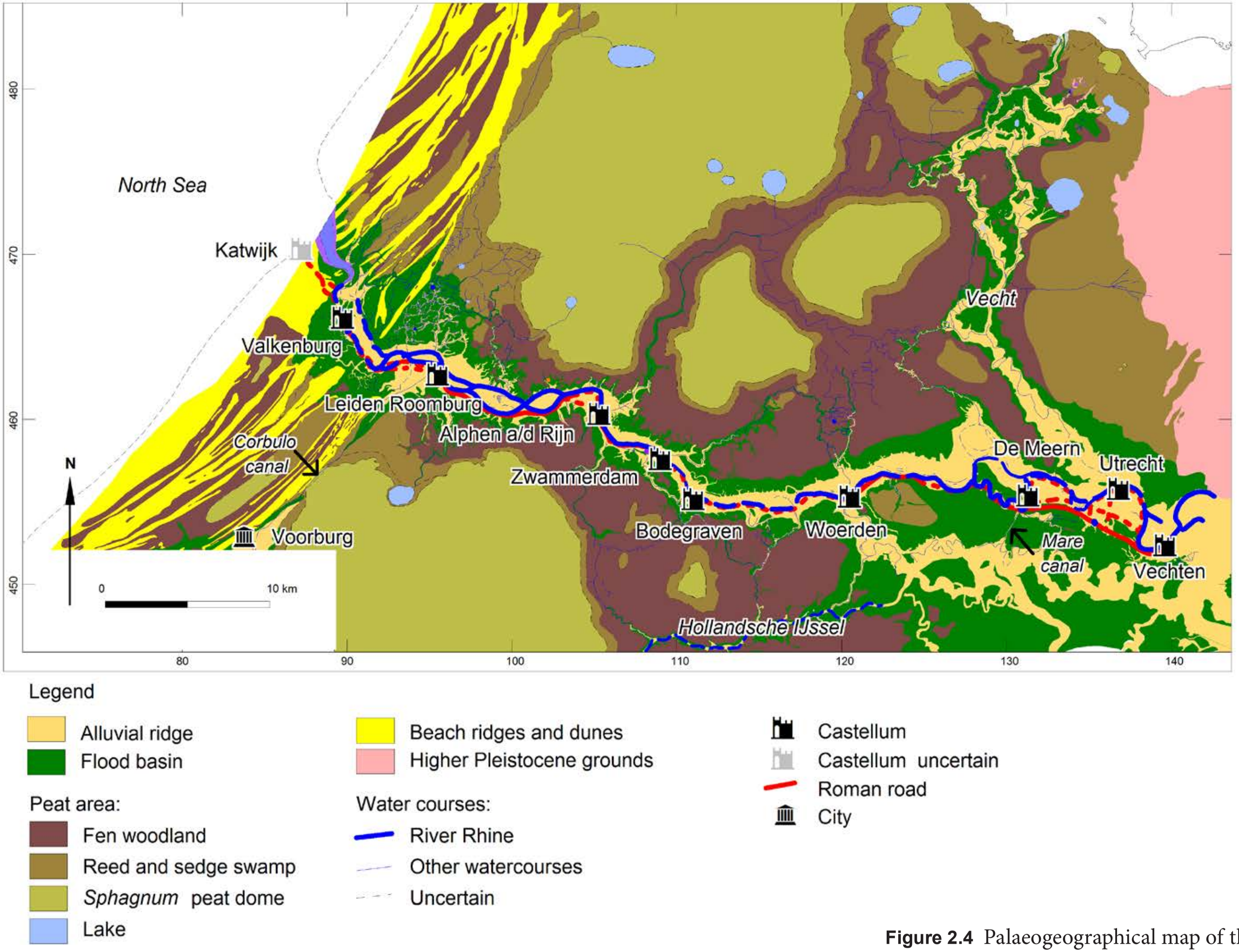


Figure 2.4 Palaeogeographical map of the study area.

Figure 2.5 **a:** Natural levee covered with alluvial forest (Doesburg, the Netherlands), **b:** Estuary with sand banks and flanked by salt marshes (river Nith, Scotland, UK; photo: Scottish Environment Protection Agency), **c:** Productive grasslands in flood basin (Tulcea, Romania; photo H. Weerts), **d:** Fen woodland (Barneveld, the Netherlands), **e:** Peat bog (Kemeru National Park, Letvia; photo H. Weerts), **f:** Dune valley in between dune ridges (Burg Haamstede, the Netherlands; photo H. Weerts).

Flood basins

On either side of the alluvial ridge of the Rhine, low-lying flood basins spread out. The subsoil of these flood basins consisted of clay. In a natural situation, this area was covered with grasslands and open water (Fig. 2.5c; De Klerk *et al.,* 1997 a; 1997b). The width of these flood basins in the research area varied considerably. In the eastern part of the research area the basin reached a width of around two kilometres, whereas it was only a few hundred meters wide in the central part between Woerden and Alphen aan den Rijn. Near Leiden, it widens again to over 4 kilometres with complex drainage networks.

Peat lands
Further away from the alluvial ridge, behind the distal parts of the flood basin vast peat lands stretched out (Fig. 2.4). In most parts of the research area, extensive fen woodlands occurred behind the flood basins (Fig. 2.5d). Studies on wood remains from this peat area show that an Alno-Padion woodland with alder (*Alnus*) and small percentages of oak and ash were present here in Roman times (M. Kooistra *et al.,* 2006; Fokma, 1998; Jansma, 1995; Visser, 2009; Bouma et al., 2011). Mean annual groundwater levels usually varied between 10 cm above and below the surface (Stortelder *et al.,* 1998).

The nutrient concentration in the groundwater in the forested fens gradually decreased away from the rivers. Consequently, the nutrient rich fens changed gradually into poor ones, subsequently into transitional mires consisting of mesotrophic reed and sedge swamps, and ultimately into nutrient poor *Sphagnum* peat bogs (Fig. 2.5e). These vast peat domes often measured over several kilometres in diameter, probably raised c. 4-5 meters above the surrounding area, and thereby released a fair amount of drainage water (Pons, 1992; Westerhoff *et al.,* 2003; De Bont, 2008). A complex network of small watercourses received this drainage water and transported it to the rivers Rhine and Vecht. The existence of these brooks, so-called peat rivers, was already known, but hitherto it was assumed that these rivers developed individually in the peat area and were not connected to each other (Fig. 2.2). However, the curved ditch patterns visible on historical topographical maps extend much further into the former wetland area, indicating that the former peat rivers not only were much longer, but even formed an interconnected network in the vast fen woodlands both north and south of the river Rhine (Fig. 2.4; Appendix A).

Delta borders
In the north-east, the delta was bordered by higher Pleistocene ice-pushed ridges and aeolian cover sands raising up to 30 meters height above sea-level. On the western side, the delta was bordered by a coastal zone consisting of series of beach ridges with low dunes and barrier plains with peat formation (Jelgersma *et al.,* 1970; Van Staalduinen *et al.,* 1979; Westerhoff *et al.,* 1987). The gently undulating dunes raised only a few metres above the surrounding plains. The natural vegetation consisted of dune shrub of Sea Buckthorn (*Hippophaë rhamnoides*), Common Juniper (*Juniperus communis*), Hazel (*Corylus avellana*) and Oak (*Quercus*), while in the low-lying plains between the dunes fen woodland and reed-sedge swamps were present (Fig. 2.5f; Jelgersma *et al.,* 1970; De Jong and Zagwijn, 1983; Bakels, 2008; Kooistra, 2009). Only in the centre of the broadest plains, nutrient poor conditions prevailed, so here small peat bogs could develop (Stichting voor Bodemkartering, 1982). It is assumed that the shoreline near the Rhine estuary in Roman times was located some 400 meters offshore of the current fore-dunes (Bloemers and De Weerd, 1984; De Weerd, 1986).

2.4.2 Landscape dynamics

River floods
Floods were annual phenomena in the delta. Peak discharges of the Rhine mainly occur in winter to spring resulting from precipitation excess and snow melt (Middelkoop and Van Haselen, 1999; Middelkoop *et al.,* 2001). During average peak discharges, the lower parts of the natural levees and the flood basin were inundated. The highest parts of the levees were only flooded during extreme

floods. Hence, these areas were used for settlement and cultivation of cereals (Groot and Kooistra, 2009; Groot *et al.,* 2009).

The natural levees bordering the river channel regularly breached during periods of high flow, resulting in the formation of crevasse splays. The palaeogeographical map shows these splays by their irregular dendritic shape, protruding from the alluvial ridge into the flood basin (Berendsen and Volleberg, 2007). During flood periods, river water also penetrated into the lower reaches of the peat brooks draining into the Rhine and Vecht rivers. Accordingly, sediment was deposited as miniature levees alongside these channels decreasing in size and thickness in 'upstream' direction towards the centre of the peat area.

The shape of the flood basins and the dimension of the floods determined how far nutrient-rich water could penetrate into these basins. This is reflected by the distribution of the fen woodlands (Fig. 2.4). This distribution shows that during the first centuries AD eutrophic river water was generally dispersed up to several kilometres behind the flood basin, while the dispersal perpendicular to the peat brooks was restricted to several hundreds meters only.

Tidal influence

In the estuary, a mixing zone between fresh and salt water occurred, with variations in water level and salt intrusion along with the tides, storms and varying river discharge. Palaeoecological studies in the western part of the research area have revealed that salt water could occasionally reach by about 15 kilometres upstream. In this freshwater tidal district, the environment only sporadically received an influx of salt water (Glasbergen, 1972; Jansma, 1988; Bult and Hallewas, 1990; Kuijper, 1990; Bakels and Stronkhorst, 2004; Kooistra, 2005; Van Zijverden, 2007; De Wolf, 2007; Van der Linden *et al.,* 2009; Van Amen and Brinkkemper, 2009). The temporal influx of salt water probably prevented the formation of an alder forest in the tidal district. Consequently, sedge swamps are present behind the flood basin in this area instead of fen woodlands (Fig. 2.4). The multiple river channel pattern that occurred in this area was presumably inherited from an earlier period in which the estuary reached further east and ebb and flood tide channels were present in this area (Westerhoff *et al.,* 2003, 225).

During each tide river discharge was blocked, causing the water level in the lower reach of the river to rise, enhancing the formation of so-called 'perimarine' crevasse splays (Berendsen, 1982). The distinct decrease in the abundance of small crevasse splays between Bodegraven and Woerden suggests that the tidal backwater effect reached up to here (Fig. 2.6). Geological and palaeoecological research in the area strengthen this assumption. An excavation three kilometres east of Alphen aan den Rijn revealed the presence of numerous channels formed by repeated levee breaching in a fresh water environment (Vos and Blom, 2004). These channels are filled with laminated sediments characteristic for the blocking effect in the lower reach of the delta plain (Berendsen, 1982). Such laminated sediments were not deposited near the *castellum* in Woerden in the first centuries AD (Van Dinter, 2008). We thus conclude that in the first centuries AD the water level in the river regularly rose as a result of blocked river discharge up to a maximum of around 30 kilometres upstream measured from the apex of the estuary.

Channel migration

Lateral channel migration in the research area was relatively small during the Roman period. Straight river stretches showed hardly any lateral channel migration (Polak *et al.,* 2004). Only in river bends lateral channel migration up to several tens of meters occurred (Ozinga et. al., 1989; Van Dinter, 2008). Nevertheless, directly downstream of De Meern a series of meander bends developed in the re-activated Heldam channel belt during the first two centuries AD In each bend, the channel gradually shifted over c. 100 meters in a period of two centuries (Van Dinter and Graafstal, 2007).

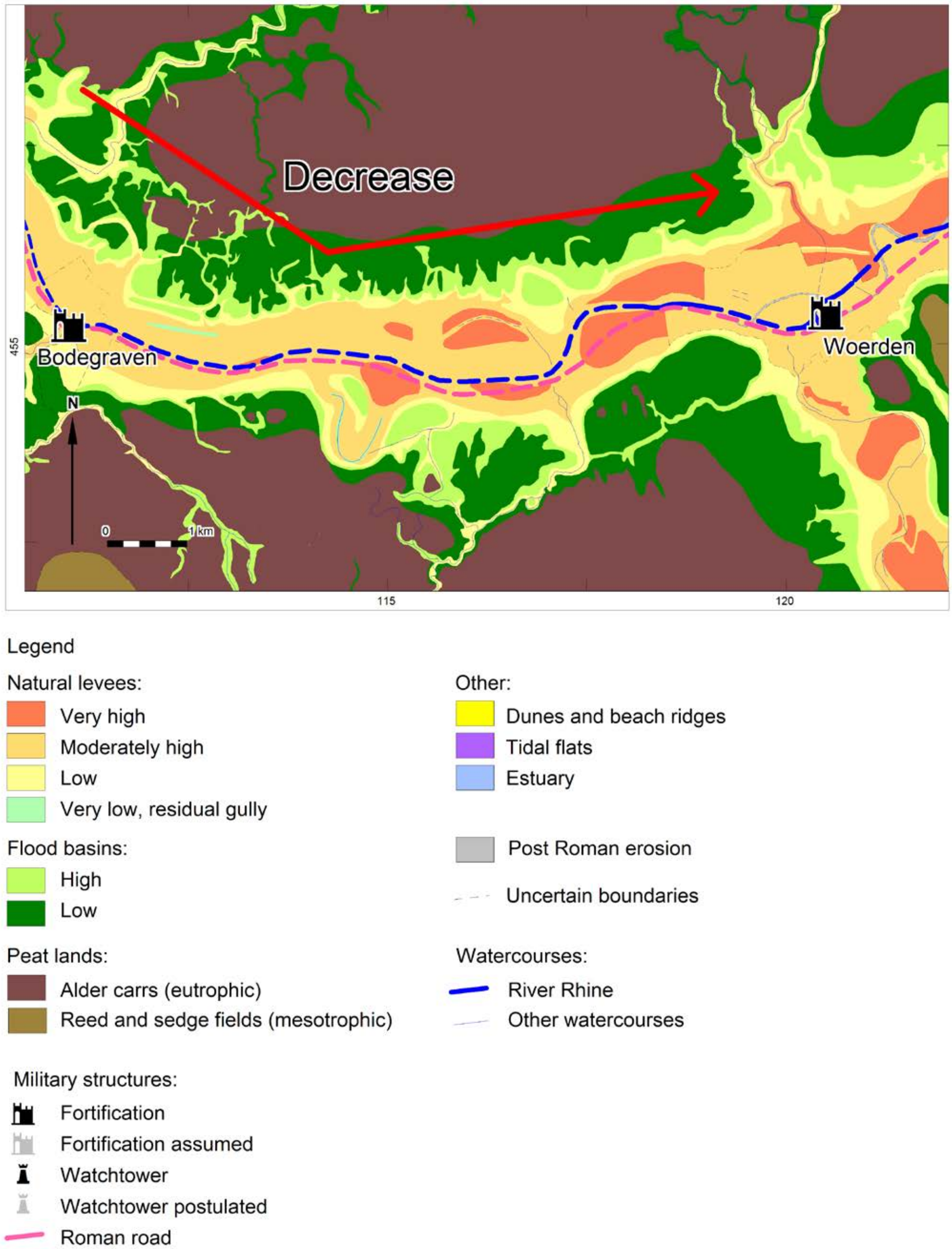


Figure 2.6 Decrease of number of crevasse splays in easterly direction. Legend also for Figs. 2.7-2.9.

Ground water flow and aeolian processes
The ice-pushed ridges in the northeast supplied a constant flow of seepage water to the low-lying river valley (Van Loonen *et al.,* 2009). The exfiltration of alkaline groundwater resulted in the formation a vast, low productive fen at the foot of these hills in the Roman Period and prevented the succession to fen woodlands and peat bogs (Van Loonen, 2010).

In the dune area significant aeolian activity occurred. Several Roman settlements and their arable fields became covered with a layer of drift sand (Waasdorp, 1998; Van der Velde, 2008). This can only occur if at least parts of the dunes were not vegetated, probably due to agricultural use (Weerts *et al.,* 2011). Deforestation of the beach barriers in this period is indeed reflected in pollen diagrams from the dune area (Kooistra, 2009).

2.4.3 Military structures

Forts
All Roman forts were built on the southern natural levee of the river Rhine, with the long fronts of the *castella* facing the river. In many cases, clusters of timber pole remains were found at a distance of only 10-15 meters from the *castellum* wall. These are interpreted as the remains of water front installations such as revetments, simple quays or mooring stages (Haalebos, 1977; 1998; Hazenberg, 2000; Polak *et al.,* 2004; Van der Kooij *et al.,* 2005; Lesparre-de Waal and De Kort, 2006). This implies that the forts were positioned almost directly adjacent to the river channel (Fig. 2.7). The majority of the *castella* was erected directly alongside or directly opposite the mouth of peat brooks: the Woerden fort was built opposite the Grecht, the Bodegraven fort alongside the Oude Bodegraven, the Zwammerdam fort opposite the Meije, the Alphen aan den Rijn fort opposite the Aar, and the Leiden-Roomburg fort alongside the Vliet (Fig. 2.7d-h). The fort in Utrecht was positioned at or close to the river bifurcation of the rivers Rhine and Vecht (Fig. 2.7b).

The three remaining forts of De Meern, Valkenburg and Katwijk were, likewise, erected at specific positions in the landscape as well. The fort in De Meern was built at the junction of two alluvial ridges: the Oude Rijn and the Heldam ridge (Fig. 2.7c). The river in the Heldam branch was active during the Roman Period. However, it is uncertain whether the northerly Oude Rijn was active at this time. If so, the river bifurcation of the Oude Rijn and Heldam river was situated approximately 1 kilometre north of the De Meern fort (Aarts, 2012). The fort in Valkenburg (*Praetorium Agrippine*) seems to have been built near the apex of the estuary, on the first location where the natural levees of the Rhine were broad enough and not prone to daily flooding (Fig. 2.7i). Finally, the fort near Katwijk, presumably Brittenburg or *Lugdunum*, was lost due to retrograding of the coastline in post-Roman times, but was most likely built in the dune area at the south-western border of the estuary (Fig. 2.7j).

Remarkably, most forts were not built at the highest sites that were less prone to flooding, as was hitherto presumed (Bechert and Willems, 1995). The *castellum* in Alphen aan den Rijn was even built in a low-lying residual channel (Kok, 2000; Polak *et al.,* 2004). Plant remains unearthed in the soldiers barracks demonstrate that damp conditions prevailed in the fort during its usage. Some forts were positioned less than a few hundred meters away from higher levee plateaus (Haalebos and Franzen, 2000; Blom and Vos, 2008; Duurland, in press).

The erection of forts directly along the waterside inevitably made them vulnerable to flooding. Evidence of flooding and devastation has been demonstrated in several forts and their surroundings (Glasbergen, 1972; Bult and Hallewas, 1990; Ozinga *et al.,* 1989; Polak and Wynia, 1991; Hessing *et al.,* 1997; Polak *et al.,* 2004; Van Dinter, 2008). Sand lenses regularly found in the forts and their surrounding ditches reflect the occurrence of flood events. Sometimes, even washed-away objects and construction parts, such as writing tablets, wattle, tent pegs, and wooden doors, were found in these layers (Polak *et al.,* 2004). Unfortunately, most layers could not be dated very accurately. Nevertheless, there are indications of a severe flood in the early 40s AD (Bogaers and Haalebos, 1987; Hessing *et al.,* 1995; Polak, 2006; Blom and Vos, 2008). Synchronicity of other severe floods that must have occurred along the Rhine and affected the forts could not be determined.

The fort at Vechten was built on a natural levee along the concave bank of the Oudwulvenbroek meander in the Rhine (Fig. 2.7a). The Oudwulvenbroek river channel started to silt up during the Roman occupation phase, probably as early as the second half of the 1st century AD (Polak and Wynia, 1991; Van Tent and Vogelenzang, 1996; Polak, 2006). Based on toponymic arguments it is commonly believed that the fortification in Vechten was built near the bifurcation node of Rhine and Vecht (Polak and Wynia, 1991; Bechert and Willems, 1995; Hessing *et al.,* 1997). However, the residual channel of the Oudwulvenbroek downstream of fort Vechten is situated along the edge of the meander belt, thereby ruling out the possibility that a river bifurcation was located within c. 3 kilometres distance downstream of the fort (Fig. 2.7a). A bifurcation node just upstream of the *castellum* is unlikely as well, as the entrance of the Vecht channel would have been almost perpendicular to the Rhine, thereby inhibiting the inflow of water. Furthermore, both rivers would then have nearly converged downstream of the Oudwulvenbroek meander bend. Hence, it is more likely that the bifurcation of Rhine and Vecht was located in the city of Utrecht during the early 1st century AD, presumably at the fort at Utrecht (Fig. 2.7b).

The abandonment of the Oudwulvenbroek residual channel probably coincided with the silting-up of the upstream Zeist meander (Berendsen and Wynia, 1993; Berendsen and Stouthamer, 2001). In this way, the silting-up of both channels can easily be explained by a river avulsion that occurred c. 1.5 kilometres upstream of the *castellum* around the middle of the 1st century AD (Fig. 2.7a). The clayey and peaty fill of the proximal part of the abandoned channel indicates that the water supply through the Oudwulvenbroek channel was suddenly interrupted (Toonen *et al.,* 2012; Jansen *et al.,* 2014). Yet, the location of fort Vechten did not change after relocation of the channel. Driessen (2007) proposed that some military and civilian settlement locations remained in use at an initial setting because the effort required to give up a selected and organised foothold and set up a new one was too high. This so-called 'path dependency' might also apply to fortifications in Vechten. Nevertheless, a new, smaller military post might have been built at the cut-off point to watch over the newly formed channel (Fig. 2.7a).

The path-dependency mechanism might also be applicable to the consecutive fortifications in Woerden. Although only a small part of the fortifications has been excavated, its first establishment is dated early-Claudian (AD 41-47) or even earlier, under the reign of Caligula (Blom and Vos, 2008). As no sign of any buildings have been unearthed (yet), it is postulated that it only achieved the state of an enforced encampment with tents. Shortly after its erection, the camp was flooded and covered under a layer of sediment (Van Dinter, 2008). Subsequently, a new fortification was built during the later '40s. This new *castellum* was erected several tens of metres to the east of its precursor, while the plan form was rotated 10 degrees in clockwise direction (Blom and Vos, 2008). This reorientation suggests that a slight change in the position of the river channel or the mouth of the Grecht had occurred. The discovery of a sunken Roman vessel and a sequence of bank enforcements north of the *castellum* revealed that the river bend continued to shift in northwestern direction during the 1st and 2nd century AD. By the end of the 2nd century AD, the channel had moved just over 50 m (Haalebos, 1998; Van Dinter, 2008). Yet, the successive *castellum* phases were erected at the same location as the second phase, which again might be explained by path dependency.

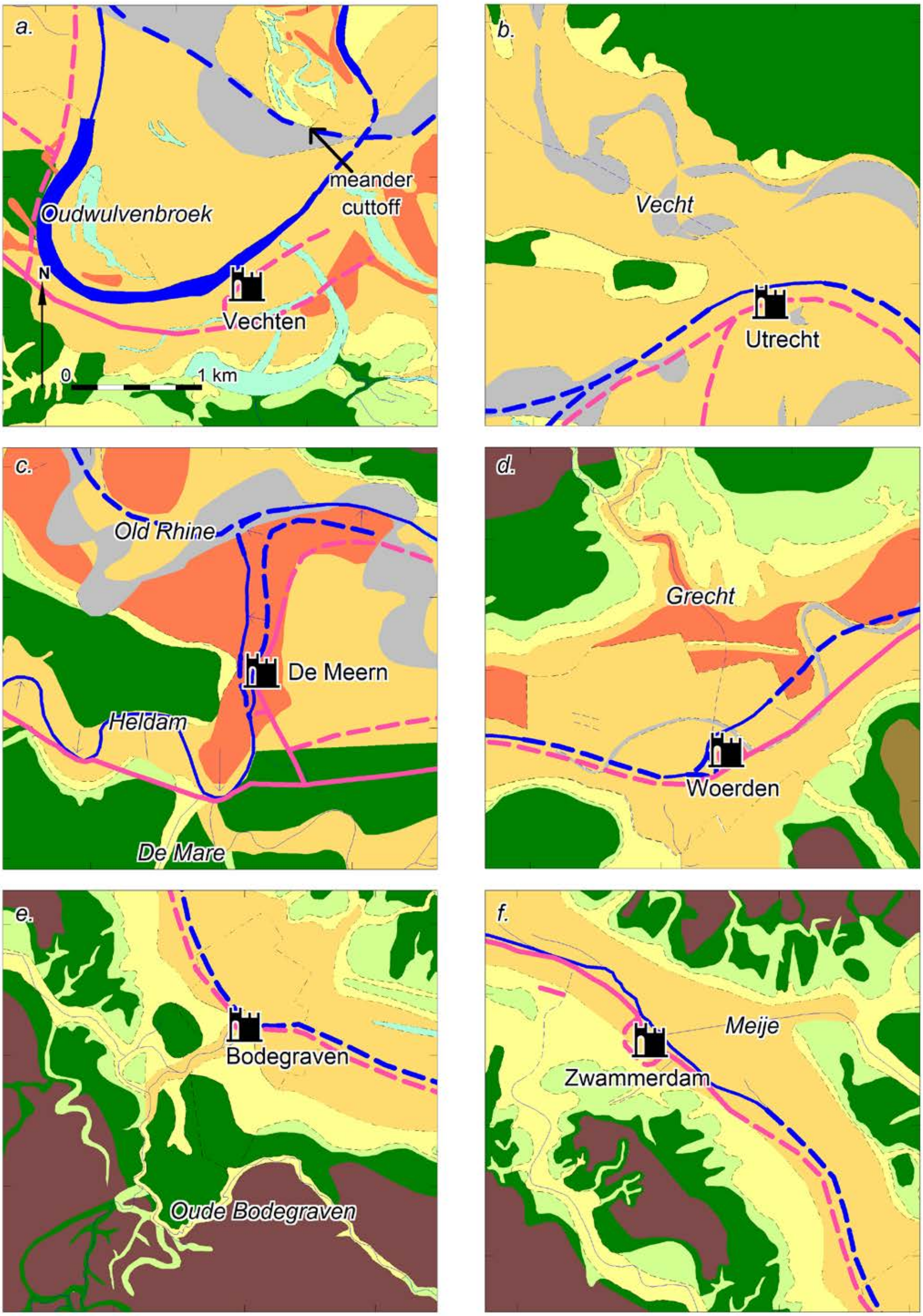
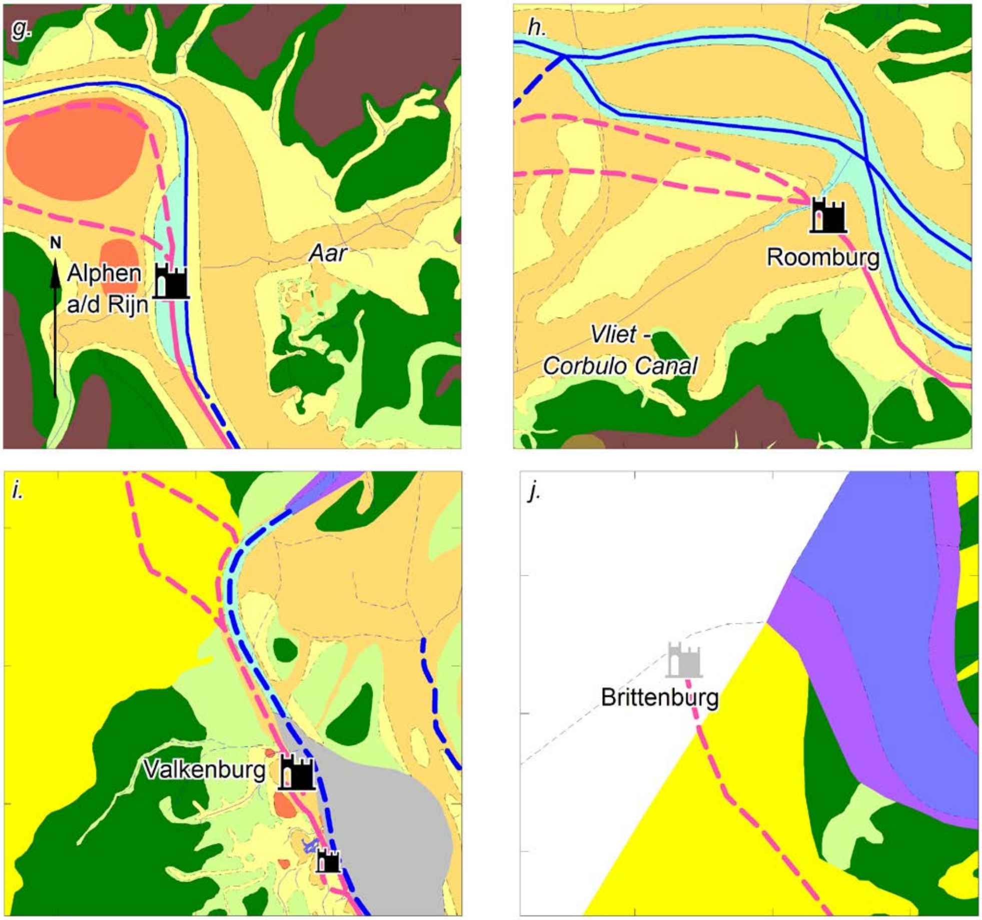


Figure 2.7 Palaeogeographical situation in the surroundings of the Roman *castella* along the western Lower Rhine in first centuries AD (For legend see Fig. 2.6).



*Watch*towers

Watchtowers were considered rare phenomena along this part of the *Limes*-zone (Van Dierendonck, 2004). Until recently, only one defended watch or signal tower adjacent to a small fortlet was revealed to be located c. 1 kilometre upstream of fort Valkenburg (Fig. 2.8). The tower and fortlet presumably functioned both during the last quarter of the 1st century AD, but most likely not simultaneously (Van Dierendonck, 2004).

Recently, three watchtower complexes were discovered near fort De Meern (Fig. 2.9a). One tower was built c. 1 kilometre north of the *castellum* and at least two watchtowers were erected along the strongly meandering river downstream of the fort at c. two kilometres intervals in the middle of the 1st century AD (Van der Kamp, 2007; Langeveld and Luksen-IJtsma, 2010; Wynia, 2004). The towers were constructed out of timber and earth, they had a square plan form with c. 3.5 meters long sides and were surrounded by a wooden palisade and a ditch with pointed stakes. The towers were rebuilt several times and functioned at least until the seventies of the 1st century AD (Van der Kamp, 2007; Langeveld and Luksen-IJtsma, 2010). Based on the size, depth and distance between the corner posts, the towers were presumably two-storey buildings. The younger tower built on

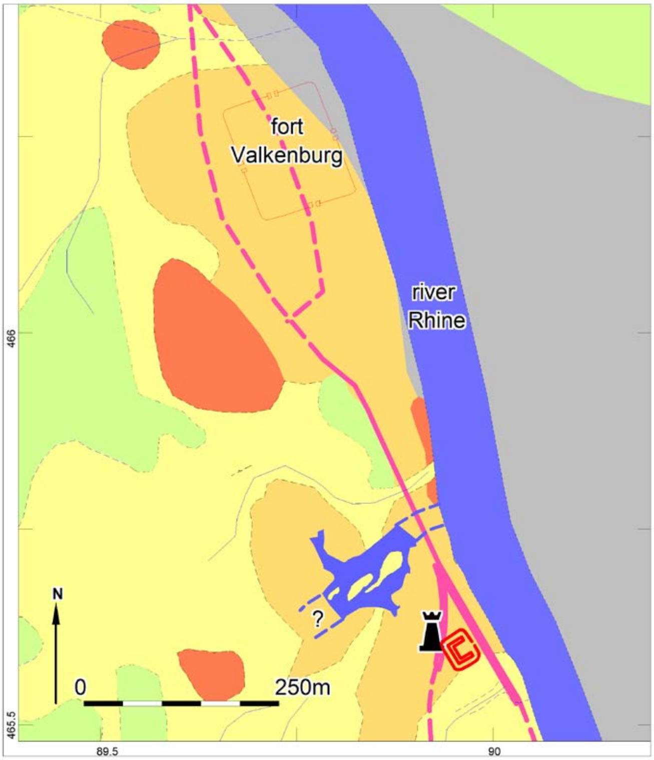


Figure 2.8: Location of fortlet and watchtower south of fort Valkenburg (For legend see Fig. 2.6).

top of the earlier one at the westernmost site was probably a three-storey building (Van der Kamp, 2007).

The towers were not erected on the highest parts of the natural levee, but close to the river, overlooking a large stretch of river. The tower north of the fort De Meern was built ahead of a sharp river bend, while the two towers downstream of the fort were located on the southern levee and at the lower end of subsequent meander bends (Fig. 2.9a). Evidence for the presence of a raised platform was lacking (Langeveld and Luksen-IJtsma, 2010). Furthermore, the youngest phase of the easternmost site along the Heldam river was erected c. 30 meters to the west of its precursor (Fig. 2.9b-c; Langeveld and Luksen-IJtsma, 2010). In the meantime, the river bend had shifted its position over a comparable distance and in a similar direction. By the end of the 1st century AD this complex was partly destroyed due to ongoing river migration and no trace of a new tower complex was discovered (Fig. 2.9c).

Roman road

The *Tabula Peutingeriana*, a medieval copy of a Roman itinerary originating from the reign of Diocletianus (AD 284-305), shows the presence of a road along the river Rhine, *fl(uvius) R(h)enus* (Fig. 2.10). The map also reveals the mutual distances between fortifications in the Dutch river delta. The distances between the *castella* in the Lower Rhine Delta are irregular and relatively short; usually less than half a day's march, sometimes even only one hour walk (Table 2.1).

The earliest archaeologically recognisable traces of proper land infrastructure date to the eighties of the 1st century AD (Luksen-IJtsma, 2010). The road ran south of the river, mostly on

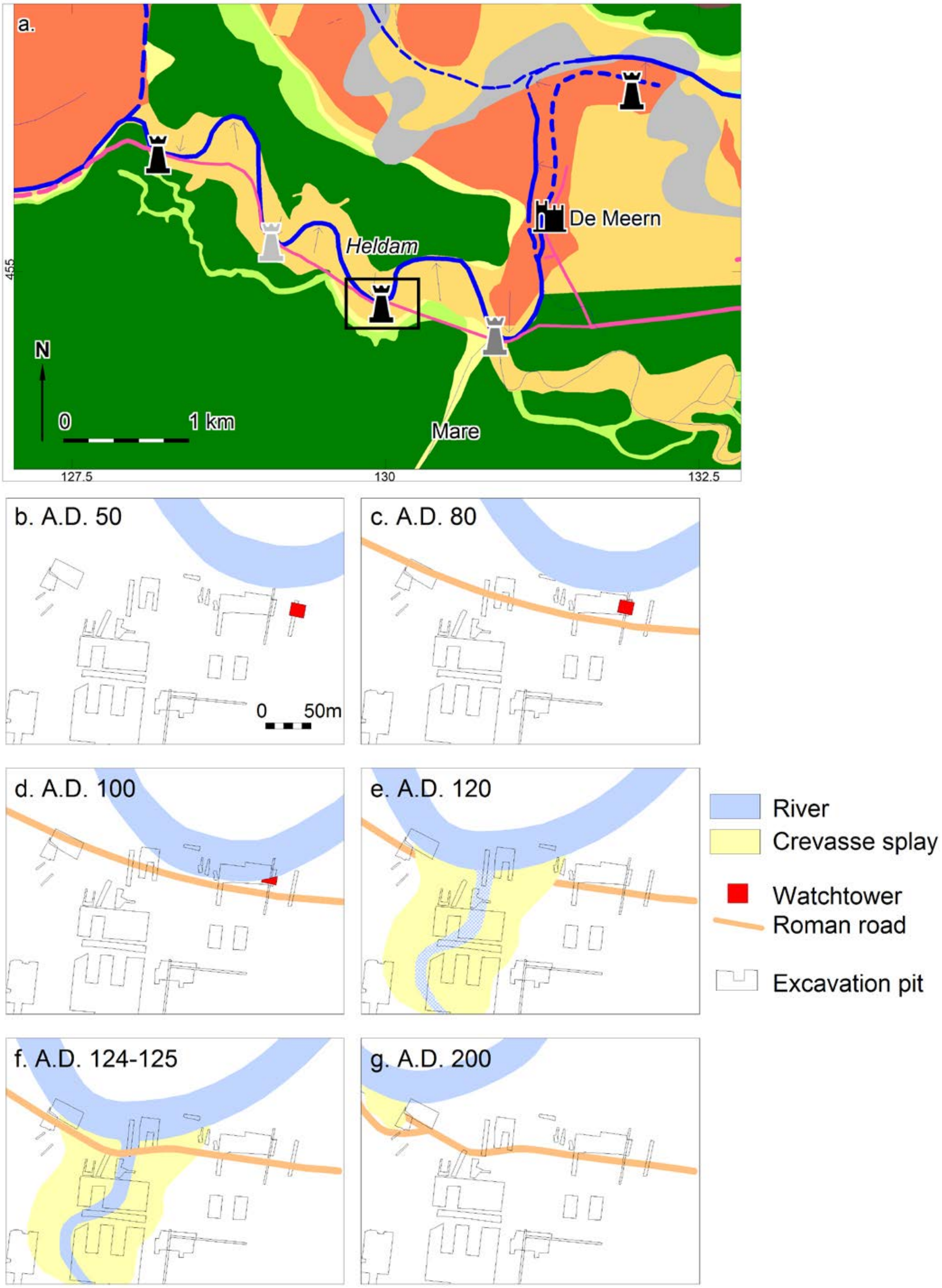


Figure 2.9 a. Distribution of military complexes near fort De Meern (For legend see Fig. 2.6); b-g: River migration along the eastern most watchtower complex along the Heldam river through time (box in Fig. 2.9a indicates location).

Figure 2.10 Part of *Tabula Peutingeriana* segment 1, depicting rivers, roads and fortifications with mutual distances in *leugae* in the western part Lower Rhine Delta (Weber, 1976).

the natural levees of the river Rhine, but some parts were constructed in the flood basin. (Luksen-IJtsma, 2010). The road was kept as straight as circumstances permitted, cutting short river bends (Fig. 2.4). The *castella* could be reached by branch roads. Sometimes, floodings and river bend migration damaged parts of the road. Subsequently, bypasses were built to overcome the damage (Fig. 2.9d-g; Hallewas and Van Dierendonck, 1993; Vos and Lanzing, 2000; Hissel, 2008; Van der Kamp, 2009; Langeveld, 2011; Weterings and Meijer, 2011). When the distances on the Tabula are compared to the length of the reconstructed road sections, it becomes obvious that the distances are approximately similar, implying that the present identification of the forts along the Lower Rhine is trustworthy (Table 2.1).

The Roman road usually was 4-6 meters wide, on a low dyke of sand, clay and sods, bordered by one or two ditches and paved with gravel, fragmented roof tiles and/or shells (Luksen-IJtsma, 2010). As gravel is not naturally present in this part of the delta, the material must have been shipped in from elsewhere, most likely from upstream pits (Aalbersberg, 2004; Dijkmans, 2004). The shells that occasionally were used for paving were collected near the sea shore and must have been transported upstream (Kuijper, 1990; Ploegaert, 2006). The road in the research area seems to have functioned until the early 3rd century AD (Luksen-IJtsma, 2010).

Table 2.1 Comparison of distances between *castella* on *Tabula Peutingeriana* and palaeogeographic map, * 1 *leuga* = around 2,2 kilometres

	Tabula Peutingeriana		**Palaeogeographic map**	
	leugae*	**km**	**In km**	
Vechten (*Fletione*) – De Meern (Utrecht – De Meern) De Meern – Woerden (*Laurium*)	12	24.4	8.7 (6.8) 13.6	22.3
Woerden – Bodegraven	5	11.2	10.2	12.8
Bodegraven – Zwammerdam (*Nigropullo*)			2.6	
Zwammerdam (*Nigropullo*) – Alphen aan de Rijn (*Albaniana*)	2	4.4	5.1	
Alphen aan de Rijn (*Albaniana*) – Leiden Roomburg (*Matilone*)	5	11.2	~ 12	
Leiden Roomburg (*Matilone*) – Valkenburg (*Praetorium Agrippine*)	3	6.6	7.8	
Valkenburg (*Praetorium Agrippine*) – Katwijk (*Lugduno*)	2	4.4	~ 5	

Canals
At least two canals were dug during the first centuries AD: the Corbulo canal and the Mare canal (Fig. 2.4; Van Dockum, 1997; Hessing *et al.,* 1991; Vos, 2007; De Kort and Raczynski-Henk, 2008). By digging a relatively short canal through the watersheds the canals linked existing channels. In this way, the Corbulo canal connected the Rhine to the Gantel/Meuse and the Mare canal connected the Rhine to the Hollandsche IJssel. Due to the subsequent water flow and resulting erosion it is hard to prove that the canals were initially dug by man (Cohen *et al.,* 2009). Nevertheless, relicts of spade cuttings were discovered in the Corbulo canal (Fig. 2.11; De Kort and Raczynski-Henk, 2008). Near the mouth of the Mare canal in the Rhine, c. one kilometre south of fort De Meern, a small military complex is assumed (Jansen, 2006). Yet, the exact outlay and dating of this feature is still unknown (Fig. 2.9a).

2.5 Discussion

2.5.1 Forts
This study demonstrates that the *castella* built in the western Lower Rhine Delta from the early 40s AD onwards were erected at strategic positions in the landscape. Not only the major river bifurcation of the river Rhine with the river Vecht and the estuary were guarded, but also seemingly minor nodal points in the river system, i.e. the junctions with small peat brooks. In contrast to earlier assumptions, these small rivers were not used as harbours (Bechert and Willems, 1995), but they formed an interconnected network of waterways, thereby creating uninterrupted natural transport routes from the Rhine to the river Vecht in the north as well as the Hollandsche IJssel and further to the river Meuse in the south. In contrast, the entries of crevasse channels that ended in the flood basins were not guarded and sometimes used as harbour (Hallewas and Van Dierendonck, 1993; Vos and Blom, 2003). Apparently, only entry points through which military trade and expeditions to the north could be performed were watched over. These waterways could not only be used by the Roman army to reach Germanic residential areas further north, but also formed the easiest passageways through which potential enemies could enter this part of the Rhine delta as well. As the vast wetlands behind the natural levees of the Rhine were almost uninhabited and thus provided no threat, these enemies must have come by boat from far distances, like Frisia for example (Fig. 2.2). It appears that penetration and raiding of the delta was prohibited by guarding all bifurcations of continuous navigable transits to the river Rhine.

The *castella* were erected directly alongside of the river irrespective of terrain height. Apparently, the accessibility of the forts by boats and the view over the river were more important than the increased risk of floodings and the presence of a firm soil. The moorings and landings stages in front of the forts facilitated the unloading of soldiers and provisioning from the boats. Thousands of shiploads a year were necessary to provide the Roman Rhine army with food and building materials in the 1st century AD (Konen, 2008). The river was suitable for large-scale transportation of material as well as people, being cheap and fast, at least in a downstream direction (Sommer, 2009). Until recently, it was generally assumed that the wooden barges used for transport only served as 'packaging' for the cargo before its wood was re-used in the delta (Bazelmans *et al.,* 2007). However, recent research has shown that Rhine transport was not an exclusive downstream traffic (Moeyes, 2007). Some of the recently unearthed Roman vessels had a surprisingly long lifespan, sometimes even several centuries (Jansma and Morel, 2007; Blom *et al.,* 2008). They were not only fitted with sails, but it is currently proven that they could easily be punted, hauled and rowed upstream

(Moeyes, 2007). Besides, some vessels possessed oar arrangements and they might have been built in the Dutch delta (Jansma, 2007; Vos *et al.,* 2011). The fact that a proper military road along the Rhine was only established at the end of the 1st century AD, once more confirms the hypothesis that the river was the main transport corridor in Roman times (Polak, 2009; Sommer, 2009; Graafstal, 2017).

2.5.2 Small military complexes

Free-standing watchtowers and fortlets in between the *castella* seem to have complemented the defensive system in the Rhine delta in the second half of the 1st century AD. In contrast to other frontier zones of the Roman Empire, the functioning of the 1st century AD watchtowers markedly preceded the construction of the Roman road, consequently excluding a connection between the watchtowers and Roman roads in the Rhine delta in the 1st century AD (contra Woolliscroft, 2001). Yet, the locations of the watchtower complexes near De Meern and the assumed small military complex at the mouth of the Mare were chosen in such a way that the river bends in between the forts could be over-seen. The reallocation of a tower complex following river migration at de Meern strengthens the assumption that their main aim was to over-see, monitor, and control the river. Thus, it seems that watchtowers formed an original and integral part of the concept and lay-out of the defence system along the Lower Rhine (contra Van Dierendonck, 2004).

Assistance of troops could be called for through signalling warnings or messages with flags, lights or smoke to the larger military garrisons (Woolliscroft, 2001). Signalling in Roman times is commonly assumed to be based on intervisibility with the naked eye (Baatz, 1976; Woolliscroft, 2001). Experimental archaeology has shown that the maximum determination range of light signals with the unaided eye under perfect weather conditions is two to three miles, but this range reduces dramatically with fog or rain (Woolliscroft, 2001). Therefore, it seems likely that the maximum distances at which military installations were erected securing effective signalling at all times was roughly 2-2.5 kilometres. Based on this hypothesis, together with the assumption of a complete overview over the river Rhine, other watchtower locations or small military complexes are postulated along the Lower Rhine (Appendix B). If indeed present, a varying number of watchtowers was situated in between the *castella*, up to a maximum of five. Several of these proposed towers would have been erected at a distance of more than 3 kilometres of a *castellum* and therefore could not have had direct intervisibility with a fort, similar to various watchtowers in the Wetterau *Limes* in Germany (Wooliscroft, 2001).

2.5.3 Canals

By digging at least two canals between the tributaries of the major rivers, i.e. Rhine and Meuse/ Hollandsche IJssel, not only 'the uncertain perils of the ocean' were avoided (Tacitus, *Annales* XI, 20), but it also shortened transport routes in the delta and made them less prone to piracy raiding.

2.5.4 General

It seems that the military alignment along the western Lower Rhine was primarily a river based system, at first functioning as a fortified transport corridor. The location of the forts was chosen deliberately. Strategic and logistic motives determined the location of all military complexes. All bifurcations and mouths of tributary streams that exposed the Rhine to raiding were guarded by forts, while smaller military structures in-between the forts secured a complete overview over the river. The watchtowers in between the *castella* could not only detect problems (on the river), but also transfer messages between the forts.

The remarkable small size of the *castella*, permitting the housing of one garrison of c. 500 soldiers, also seems intentional. The natural levees of the Oude Rijn were wide enough to accommodate larger forts (Fig. 2.6; contra Hessing, 1995). Apparently, their size was sufficient to fit the military purpose. If necessary, troops could quickly be transferred to neighbouring forts or other military installations.

The erection of the series of forts from the early 40s AD onwards suggests that their construction might be correlated with the conquest of Britain in AD 43 (Polak, 2009; Graafstal, 2017). This invasion involved a large-scale transport of troops and supplies and was most likely largely realized over the river Rhine. Therefore, it is likely that the Romans aimed to guard and secure this supply line. Only in the late 1st century AD the river became the real frontier zone of the Roman Empire (Polak, 2009).

The earlier Imperial fortifications upstream along the Lower Rhine as well as those along the Danube in south-eastern Europe were also erected at strategic locations (Bechter and Willems, 1985; Driessen, 2007; Sommer, 2009). However, in contrast to the Rhine delta, the forts in the river valleys were erected at elevated river terraces, protecting the forts against floodings. Driessen (2007) likewise regarded the control of the bifurcations of the Rhine between Nijmegen and Cologne, referred to as logistic nodes, important for transporting troops and material from or to hostile terrain and protection against German attacks. Sommer (2009) similarly concludes that the main purpose of forts and fortresses along the Danube in earlier Imperial Period was primarily to control the river. It seems that the fluvial landscape in general determined the distribution of military structures (contra Gechter, 2002, who considers the presence of major roads as decisive for the construction of military structures).

2.6 Conclusions

Analysis and reviewing of published (geo)archaeological data, combined with LIDAR information and coring databases allows detailed palaeogeographical mapping of the Lower Rhine *Limes* in the first two centuries AD and gives a detailed insight and understanding of the influence of the landscape on the establishment of this part of the *Limes* as a whole. Hitherto, it was uncommon to integrate results of the natural sciences of geology and biology, and the cultural science of archaeology. This study shows that interdisciplinary research can bridge the gap between these disciplines. Furthermore, it provides a framework for future research as the method used is generally applicable and therefore potentially beneficial for the future mapping of other areas and other time periods.

This study reveals the following characteristics:

1. The Roman forts erected in the western part of the Lower Rhine from the 40s AD onwards were built remarkably close together, at irregular distances only a few kilometres apart. The distinctive landscape of the Rhine-Meuse delta, with an exceptionally large number of tributaries, determined this spatial pattern. The *castella* downstream from Vechten were built on the southern natural levees of the river Rhine to guard all routes that provided natural access to the river. Not only the estuary (Katwijk, Valkenburg) and bifurcation of the river Vecht (Utrecht), but also the mouths of the numerous minor tributaries were watched over (Woerden, Bodegraven, Zwammerdam, Alphen aan den Rijn). These channels drained the peat area and formed transport routes to the river Vecht and the river Meuse. The Vecht river provided easy access to Germanic residential areas further north, while the Meuse formed the major

tributary in the delta further south. In addition, at least two canals, c.q. Corbulo and Mare, were established to create shorter and safely navigable transport routes to the Meuse. The effort to construct these waterways was minimised by digging short passages through the watersheds, thereby connecting already existing channels. The mouths of these passageways in the Rhine were also guarded by military installations (Leiden-Roomburg, De Meern).

2. All forts were erected directly alongside the river, regardless of height and composition of the subsoil, with quays and landing stages directly in front of the forts demonstrating that provisioning of troops and supplies had priority over other aspects, like the living conditions of the soldiers. The width of the natural levees did not restrict the size of the forts, implying that the remarkable small size was chosen intentionally. Between the forts, a system of small military structures, mostly watchtowers, was erected aimed at observation of river traffic.
3. It is likely that initially an integrated system of *castella* and watchtowers ensured that the river Rhine in the Lower Rhine Delta was completely watched over, just like the upper Rhine and Danube. In this way, a safe corridor was created to supply the Roman army invading Britain. Only later on, presumably after the establishment of the province *Germania Inferior* in the 80s of the 1st century AD, this corridor turned into a frontier zone. From then on, the chain of forts along the Rhine together with a coastal and Meuse estuary defensive system, protected the delta and Roman Empire from Germanic invasions.

3 Settlement and land use on crevasse splay deposits; geoarchaeological research in the Rhine-Meuse Delta, The Netherlands

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3.1 Introduction

Since the 1950s, Dutch archaeologists widely agreed on the idea that prehistoric occupation in the Dutch river area only occurred on channel belts and aeolian dunes (Modderman, 1949a, 1949b, 1955; Pons and Modderman, 1951). Soil scientists, however, showed that prehistoric sites in this area were also situated further away from the channel belt, in particular on crevasse splay deposits (Pons, 1953; Havinga, 1969, 1993; Havinga and Op 't Hof, 1975, 1983). They attributed the occurrence of these crevasse sites to the relatively high position of these deposits in the alluvial landscape during and shortly after the time of formation. However, this idea was not generally recognised among the majority of the Dutch archaeologists. Only a few excavations were carried out where a-priori knowledge existed that a Bronze Age settlement was situated on crevasse splay deposits; an example is the excavation 'de Hien' near Dodewaard (Hulst, 1967, 1970, 1991). Also Louwe Kooijmans (1974, 1985) confirmed the presence of prehistoric human occupation on crevasse splay deposits. Still, large scale archaeological excavations in the Rhine-Meuse Delta near Wijk bij Duurstede ('de Horden') in the 1970s and 80s showed that this idea was not commonly adopted (Hessing, 1989): during this excavation three occupation layers were found, separated by layers of sediment of varying thickness. Only during the final stages of the excavation, it was realized these were crevasse splay deposits (Hessing and Steenbeek, 1990). From this, it becomes also clear that it was not generally known that crevasse splays may occur as superimposed deposits, and that these buried sites may have excellent preservation conditions for archaeological material.

During the last two decades archaeological research in the Dutch river area has boosted because the Council of Europe drew up a treaty in Malta in 1992, called the 'Valletta treaty' or 'Malta Convention' (European Convention, 1992). This treaty aims to protect the European archaeological heritage '*as a source of European collective memory and as an instrument for historical and scientific study*'. It implies that before any disturbance of the subsoil, mainly for building activities, is going to take place archaeological investigations have to be carried out. The costs of these investigations have to be paid by the 'disturber'.

During the 1990s plans arose for the construction of a railway track between Rotterdam and Germany (called the '*Betuweroute*'), transversing the Rhine-Meuse Delta longitudinally (Fig. 3.1). The subsequent archaeological research provided an excellent opportunity to test the hypothesis that human exploitation in the delta was only sparse and seasonal, and confined to alluvial ridges and aeolian dunes, as was thought until then by the majority of archaeologists. In this chapter we synthesise the large number of excavation results that have been obtained so far, but which are

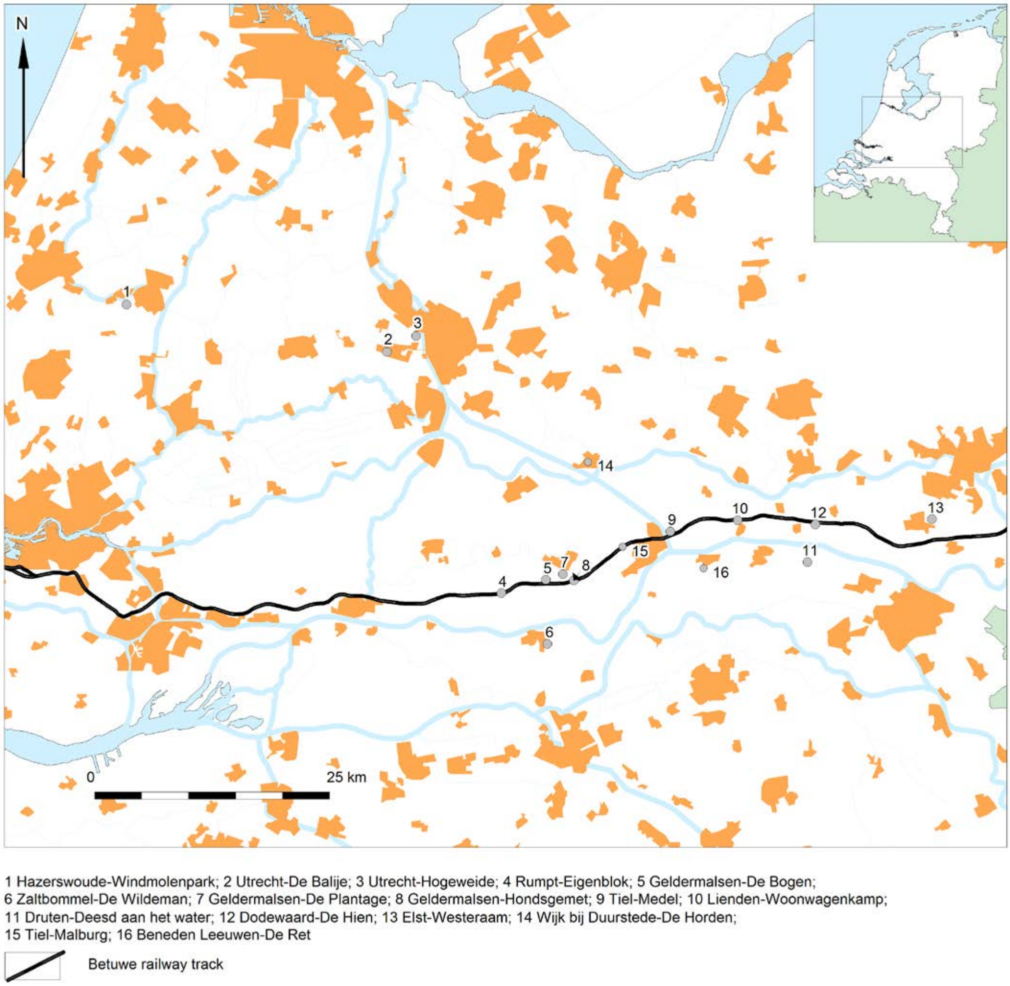

Figure 3.1 Location of the Betuwe railway track and archaeological sites mentioned in this chapter.

largely published in 'grey' literature: written in Dutch language, hard to obtain, and/or only partly published. The objective of our study was to assess whether and, if so, where human occupation occurred outside channel belts in the Rhine-Meuse delta during Neolithic and Bronze Age time. Furthermore, we aimed at determining which landscape factors determined the suitability of overbank deposits in flood basins for human occupation.

Crevasse splays

Crevasse splay deposits in the Rhine-Meuse delta

The Holocene Rhine-Meuse Delta in the Netherlands has been studied extensively over the past decades. The fluvial architecture and avulsion history is exceptionally well known, as is shown in the palaeogeographical reconstruction of the delta during the Holocene by Berendsen and Stouthamer (2001). Crevasse splay deposits form essential components of the fluvial architecture of this delta (a.o. Berendsen, 1982: Törnqvist, 1993; Weerts, 1996; Makaske, 1998; Stouthamer, 2001). Crevasse splays develop when a small channel is eroded through a natural levee during excess discharges. Subsequently, sediment is transported through this channel and deposited in the flood basin (Smith, 1983). Crevasse channels and associated splays in the Lower Rhine flood basins were first mentioned by Vink (1926; he called them 'levee bulges') and later by various soil scientists (Edelman, 1950; Pons, 1957; Havinga, 1969), who described their large variety in lithology and morphology. Berendsen (1982) started mapping and describing crevasse splay deposits in the Rhine-Meuse Delta in detail. He made a distinction between splays that were formed due to peak discharges and those that were formed due to blockage of river discharge caused by tidal influences. Since then, crevasse splays have been accepted as a fundamental architectural element in the Rhine-Meuse delta.

Crevasse splay deposits are well known for their complexity in structure, texture and geometry (Fisk, 1947; Coleman, 1969; Smith, 1983; Cross and Smith, 1985; O'Brien and Wells, 1986; Farrell, 1987; Mjøs *et al.,* 1993; Makaske, 1998). Many crevasse splays lack a well distinguishable sand body and consist largely or completely of calcareous sandy and silty clay. Often only sandy deposits are considered as splay deposits (Mjøs *et al.,* 1993). As a consequence, underestimation of 70% of the volume of the splay landform can occur (Farell, 2001). Based on the large spatial variation in the subsoil, Weerts and Bierkens (1993) suggested that accurate mapping of crevasse splay deposits in the Netherlands requires a mean coring distance of 25-30 meters. Most geological and geomorphological maps from the Rhine-Meuse delta are based on corings spaced much further apart. This implies that many crevasse splay deposits in the Netherlands are poorly mapped or, more commonly, not mapped at all.

Crevasse splay development

Smith *et al.* (1989) introduced a conceptual model of splay development consisting of three intergradational forms. Each form is associated with a characteristic sand body geometry (Fig. 3.2). Whether the breakthrough point becomes plugged, enlarges or reaches a steady state depends upon the ratio of crevasse to main-channel bed slope, height of the crevasse bottom above the bed of the main channel, and bed grain size (Slingerland and Smith, 1998). Figure 3.2 also displays active crevasse splay systems belonging to the Columbia River in NW-Canada, as an example of what a recent crevasse splay complex looks like. Farrell (2001) explored the genesis, architecture, geometry and connectivity of facies in 3D. Furthermore, she slightly revised the model of crevasse splay formation introduced by Smith *et al.* (1989) by differentiating sand facies, i.e channel and mouth bar, from heterolithic marginal and distal bar facies. Additionally, crevasse splay deposits may incise through the splay deposits into the subsurface or may non-erosively overly flood basin deposits (Makaske, 1998).

Definition of crevasse splay deposits

From Fig. 3.2b, it becomes clear that it is difficult to discriminate between crevasse splay and levee deposits when crevasse splay sediments are deposited directly behind and against the natural levee. Furthermore, crevasse splay deposits are formed by the same processes as natural levees and, therefore, their deposits do often not differ in structure and texture from levee deposits. Consequently, many splays are mapped as natural levee. In this study, crevasse splay deposits are defined as deposits in flood basins that have a coarser texture and/or an increased $CaCO_3$ content when compared to surrounding flood basin deposits. Furthermore, the distinction with levee deposits is based on the spatial distribution of the sediment. Two types of crevasse splays are distinguished: a) clear channels with bar facies that protrude into the flood basin; and b) large irregular bulges of the 'levee' indicating the presence of a sheet of crevasse splay sediments deposited directly aside levee deposits. In Fig. 3.2b both types are depicted in a present-day situation.

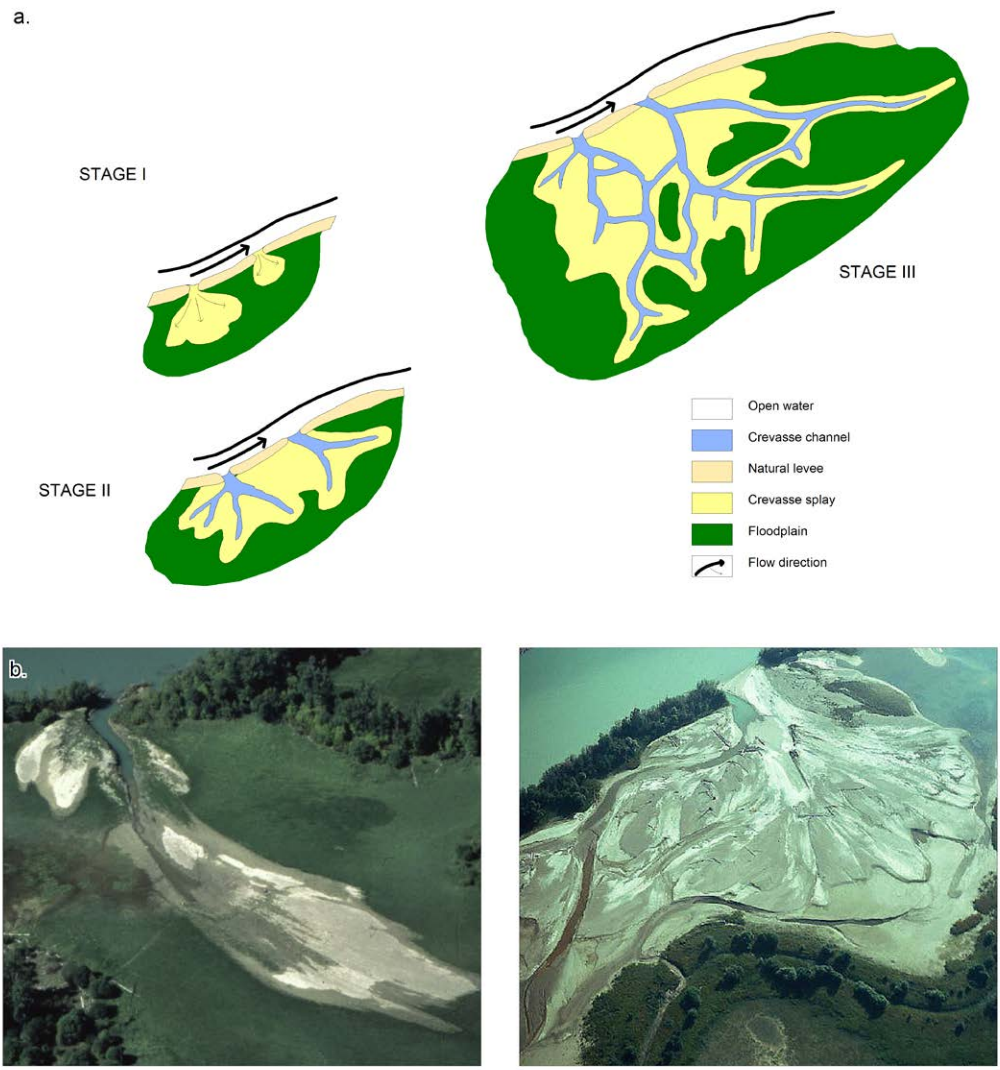

Figure 3.2 Formation of a crevasse splay complex (Smith *et al.,* 1989) and active crevasse splay systems, upper Colombia River, Canada (photo's: B. Makaske).

3.2 Methods

At first a reconnaissance study of the area concerning the planned '*Betuweroute*' railway track was carried out (Asmussen, 1991, 1994 and 1996). This research involved literature review and a coring campaign and revealed 160 archaeological sites. According to the standard criteria of the former National Service for Archaeological Heritage (ROB, nowadays the Cultural Heritage Agency) 50 of these sites should be preserved. A selection of 11 sites were excavated and the remaining were preserved *in situ*. The excavations were accompanied by extensive geological investigations that involved description of sections and detailed coring around the site. In this way, detailed information was obtained on the diversity in architecture, geometry and sedimentlogical structures in the subsoil surrounding the site.

Within approximately 500 m of each of the 11 excavation sites, corings where carried out with hand auger equipment, with spacing varying from 10 to 40 m, resulting in over 200 corings per km^2. The cores were described in the field using the methodology of Berendsen and Stouthamer (2001) at 10 cm intervals with regard to texture, median grain size, organic matter content, colour, Fe-oxide content, $CaCO_3$ content, groundwater levels and (palaeo)soils. In addition, the amount, size and diversity of archaeological artefacts was described (Isarin and van der Kroft, 2001). Archaeological artefacts are for example fragments of pottery, bone, stone, charcoal, loam, burned clay and other inclusions that naturally are not present in the subsoil. Furthermore, discoloration of the sediment, for instance caused by iron-phosphate aggregates, can indicate former occupation. Cores were numbered sequentially and the geographical location (± 5 m XY, Dutch coordinate system) and surface elevation (± 0,05 m relative to Dutch O.D. = NAP ≈ mean sea-level) were registered. Sections at the excavation were described in the same way but at 5 cm intervals.

Figures 3.4 and 3.5 are based on corings that were carried out in 1998 and 1999. Locations of the cross section in Figure 3.4 and the depicted area in Figure 3.5 are shown in Figure 3.3. Sediment bodies belonging to different crevasse splays were distinguished on the basis of depth, stratigraphy, lithology and spatial extent. The thickness of the two upper splay deposits was derived from the descriptions and interpolated with a standard interpolation using the inverse distance weighting in the thematic mapper option of MapInfo Professional 5.2 and a search radius of 30 m. Archaeological layers in corings were distinguished on the basis of the presence of archaeological artefacts in a sediment layer. Subsequently, these layers have been interpreted as farmstead, farm yard or fields/used area according to the thickness of the layer as well as the amount, size and diversity of archaeological artefacts (Groenewoudt, 1994). The finds in the excavation pits were used to control the interpretation of the coring data..

3.3 Results

Betuwe railway track

Of the 50 archaeological sites meeting the criteria of the National Service for Archaeological Heritage, three turned out to be situated on aeolian dunes and 27 were situated on alluvial ridges. The remaining 20 sites were situated on crevasse splay deposits. The investigation of sites on crevasse splay deposits provided insight in the evolution of the landscape and human settlement associated with splays. This shows that the extent of prehistoric settlement in the delta has been seriously underestimated by many archaeologists until now.

3.3.1 The excavated site near Kesteren

The 'Lienden-Woonwagenpark' archaeological site southeast of Kesteren was excavated in 1998 (Schoneveld and Kranendonk, 2002). The site was situated just north of the Westerveld channel belt (Fig. 3.3). No residual channel was found during the coring campaign. Therefore, an accurate date for the end phase of this meander belt could not be obtained. Berendsen and Stouthamer (2001) assumed that this alluvial ridge is connected to the Homoet meander belt upstream. The base of the residual channel deposits of this latter channel belt was dated 3290 ± 70 BP (Berendsen and Stouthamer, 2001). This means this channel belt was abandoned between approximately 1700 and 1400 cal BC, the Middle Bronze Age in the Netherlands. Because of the supposed correlation, this date is also presumed to be valid for the end phase of the Westerveld channel belt. The Echteld channel belt, situated south of the site (Fig. 3.3), is younger and has cut through the Westerveld channel belt.

A cross section through the excavation area (Fig. 3.4) clearly reveals several packages of crevasse splay deposits, some of which are deposited directly on top of each other. The distinction between crevasse splay and levee deposits is based on the spatial distribution of the deposits. The width of the levee deposits is fairly constant along the channel belt, whereas the crevasse splay deposits form large irregular bulges extending into the flood basin. Locally, several phases can be distinguished, deposited on top of each other. Crevasse splay deposits of phases 2 and 3 were deposited by the Westerveld channel belt. These packages consist of homogeneous sandy clay that fines upwards into silty clay and lacks any sedimentary structures. At the top of both sediment bodies a vegetation horizon occurs, that represents a phase of reduced (or absent) sedimentation, during which soil formation has started, and decalcification occurred. It thus represents an old surface and is recognisable as a black to dark-grey layer in clayey sediments (Schoute, 1984; Steenbeek, 1990). This demonstrates that the crevasse splay deposits of phase 3 generally overlie deposits of phase 2 non-erosively. Both vegetation horizons contain an admixture of sand and small pieces of archaeological relicts like pottery, burnt clay, stone and charcoal. This indicates that human activity took place on the palaeo-surfaces and, therefore, the layers are interpreted as occupation layers (Fig. 3.4). The pottery found in the occupation layer at the top of phase 2 dates to the Early Bronze Age (2000-1800 BC, Corded Ware culture, Sier and Koot, 2001). The occupation layer at the top of deposits from phase 3 were dated by ^{14}C and these dates revealed a Middle Bronze age at the transition from phase A to phase B (~ 1650-1400 cal BC; Schoneveld and Kranendonk, 2002)[1].

Figure 3.5 shows the spatial distribution of both crevasse splay bodies. In the Early Bronze Age two lobate crevasse splay bodies are present (Fig. 3.5a). Both splay bodies cover approximately 3 ha and are between 30 and 150 cm thick. Based on their planform they can be interpreted as stage I types of Smith et al. (1989, see fig.1). This type is formed by shallow, unstable channels and generally has steep edges.

Evidence of human occupation is also depicted in Figure 3.5. The thickness and occurrence of archaeological artefacts in the occupation layer in several corings suggest that a farmstead was constructed on each splay. The admixture of sand and small pieces of charcoal in the adjacent vegetation horizon suggests trampling and indicates that the entire surface of the splay was used by

1 Based on ten radiocarbon dates on wood, charcoal, bone and (food) residual left on pot sherd (GrN 15980, 16183, 16189, 24480, 25477, 25479, 25483 – 25485, 25700; results ranging between 3130 and 3270 BP), resp. eight dates from eastern settlement area and two from western settlement area.

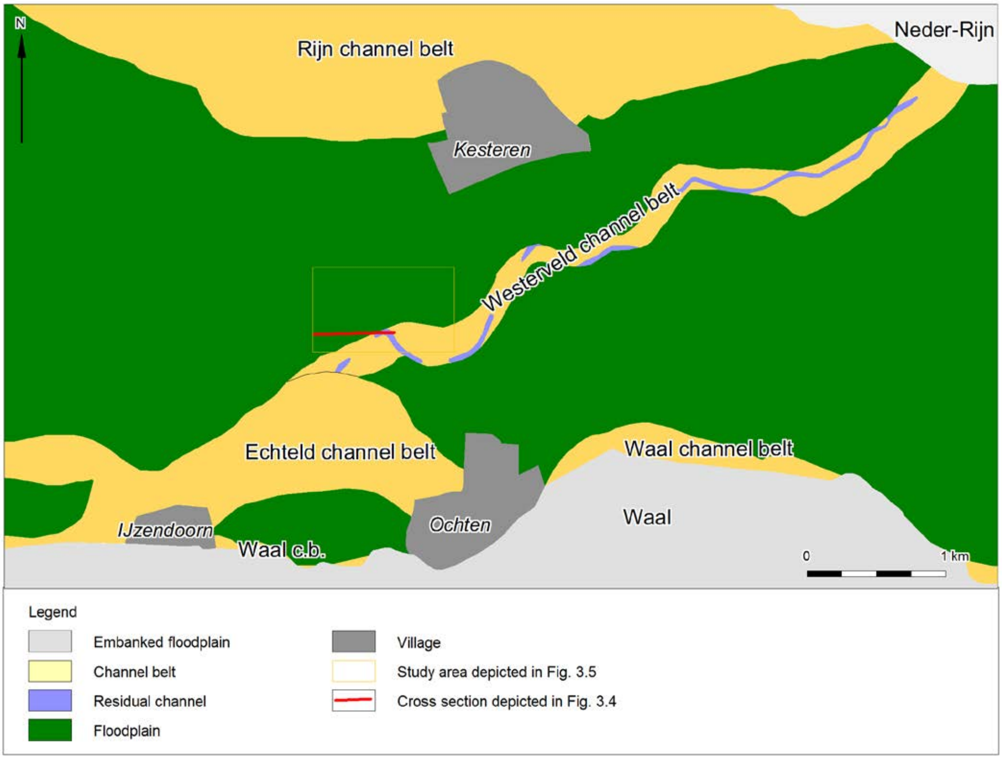

Figure 3.3 Geologic map of the area surrounding archaeological site 'Lienden-Woonwagenpark' (after Berendsen, Faessen and Kempen, 1994).

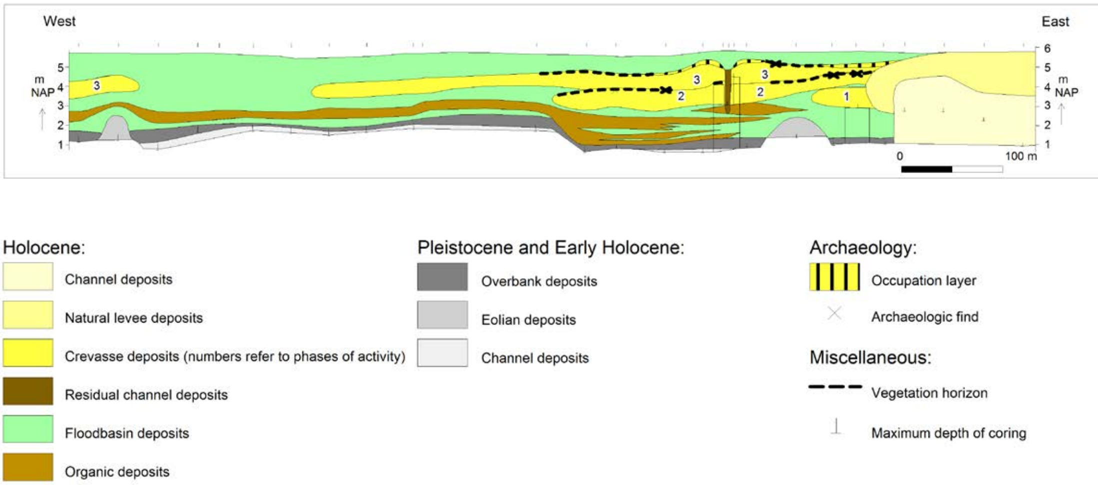

Figure 3.4 Cross section of archaeological site 'Lienden-Woonwagenpark'.

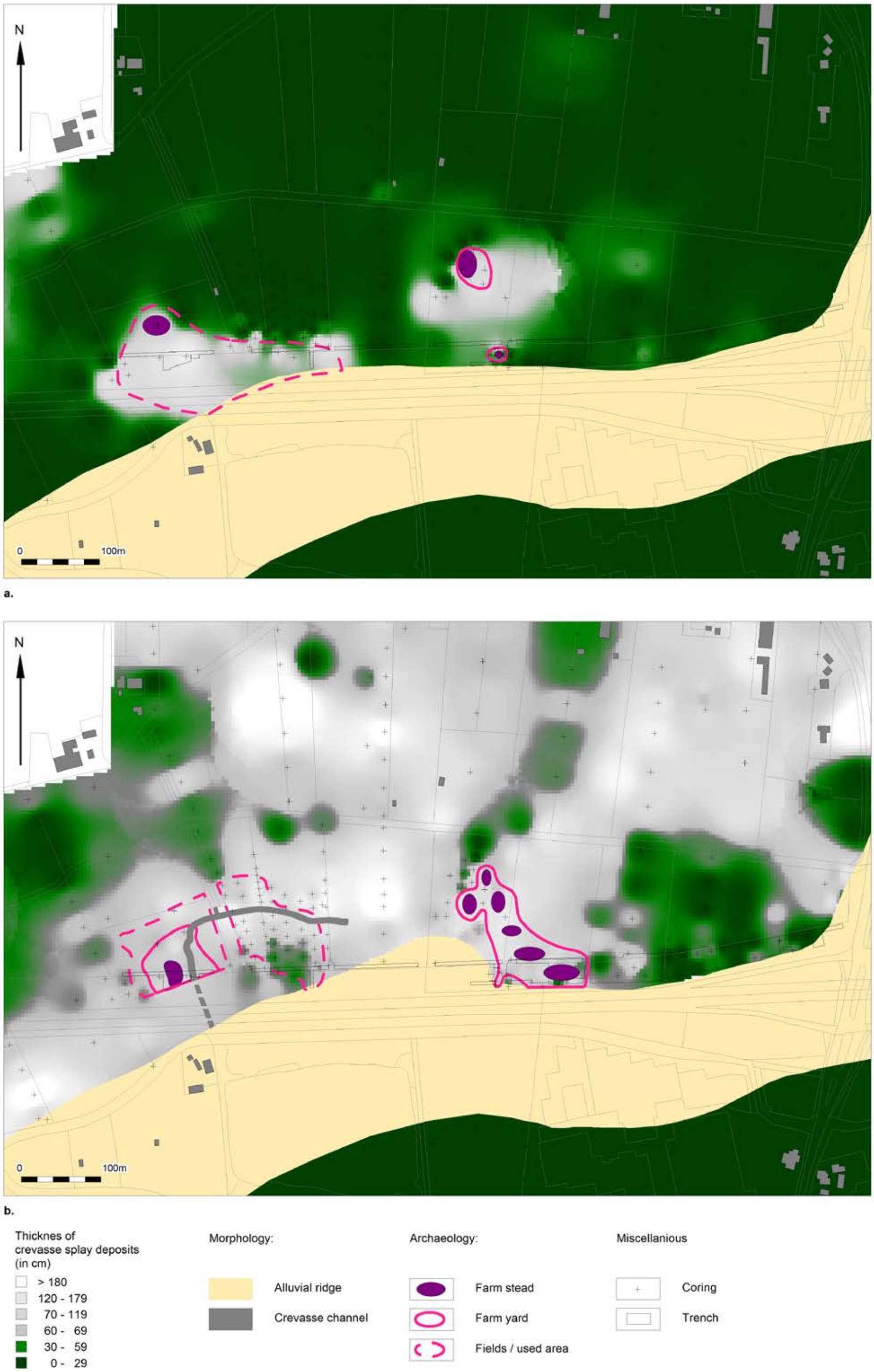
N
0
100m
a.
N
0
100m
b.
Thicknes of
crevasse splay deposits
(in cm)
> 180
120 - 179
70 - 119
60 - 69
30 - 59
0 - 29
Morphology:
Alluvial ridge
Crevasse channel
Archaeology:
Farm stead
Farm yard
Fields / used area
Miscellanious
Coring
Trench

Figure 3.5 (left) Spatial distribution of crevasse splay deposits near the archaeological site 'Lienden-Woonwagenpark'.

humans, probably for crop cultivation. These sites were not excavated, as they were not threatened by the construction of the Betuweroute railway.

The crevasse splay deposits of phase 3 are more extended (Fig. 3.5b). On the western side of the excavation area, a 400-m long and 10-m wide channel is visible. The residual channel fill is about 3 m thick and has relatively thick crevasse splay deposits on either side, resembling miniature levees (c. 50 m wide; cf. Fig. 3.4). Beyond the far end of the channel, sediment was deposited as a thin sheet over a wide area of the flood basin. Excavation in this area demonstrated that a farmstead was built on the western levee of the channel (Schoneveld and Kranendonk, 2002). Archaeological artefacts are only present in the upper part of the channel fill, showing that occupation started when the channel already ceased functioning and had started to fill. After some time, the farmstead was rebuilt on nearly the same spot. The average lifespan of a farmstead is currently assumed to be about 30 years, but recent research has shown that a lifespan of 70 to 100 years is possible (Jongste, 2008). By that time, the channel had completely filled up and could be crossed as was shown by hoof imprints present in the vegetation horizon that formed in the top of the channel fill (Fig. 3.6). This occupation phase is dated to the Middle Bronze age. On the eastern side of the excavation area, an extensive settlement area has been found. Here, several farmsteads probably existed simultaneously. Some of these farmsteads were rebuilt during the occupation phase. The occupation phases on both crevasse splay bodies were radiocarbon dated at around 3300-3100 BP and were almost certainly occupied simultaneously.

These observations reveal that crevasse splay complexes can be stacked, almost non-erosively, on top of each other. The excavation near Lienden demonstrates that occupation during the Early Bronze Age, the deposition of a crevasse splay (phase 2) and habitation during the Middle Bronze Age all took place within approximately 300-500 years. This implies that the occupation during the Early Bronze Age lasted only for a maximum of several human generations. It is not known whether a hiatus longer than the period of crevasse splay formation existed between the two habitation periods. So it remains a question whether the Middle Bronze Age people knew that their ancestors lived on the same locality.

3.3.2 Other Betuwe route excavations

Other excavations that were carried out within the framework of the Betuweroute have revealed additional information about crevasse splays complexes and human occupation. For example the excavation 'Eigenblok' near Rumpt has shown that people were willing to build a farm on a very small piece of dry ground – a crevasse splay measuring only 30 by 30 m – during the Middle Bronze Age. Here, the adjacent alluvial ridge was used for agriculture (Jongste and Van Wijngaarden, 2002). Striking was the presence of several human footprints at the edge of the crevasse splay (Fig. 3.6b). Excavation site 'De Bogen' near Meteren revealed that crevasse splay deposits of only 20 to 30 cm in thickness were apparently considered suitable for settlement (Meijlink and Kranendonk, 2002). Furthermore, a large crevasse splay complex was mapped there, that measured roughly 1 km^2. This splay was already exploited during the latest phase of the Late Neolithic period (2450-2000 BC), however this activity might (initially) have been seasonal. In the Middle Bronze Age farmsteads were built on the splay and most likely used for permanent settlement (Meijlink and Kranendonk, 2002; Arnoldussen, 2008). This human settlement lasted

Figure 3.6 a. Hoof imprints in the top of the channel fill at the archaeological site 'Lienden-Woonwagenpark', b. Human footprint in flood basin at the archaeological site 'Rumpt -De Bogen'.

uninterruptedly until the end of the Middle Bronze Age (1250 BC), indicating a period of more then 1000 years of continuous exploitation. During this period, sedimentation took place on the adjacent flood basin and on lower parts of the splay, as shown by the deposition of sediment on the lower edges of the splay, followed by the formation of a new vegetation horizon and younger archaeological features (Fig. 3.7). Thus, due to subsidence, the available arable area reduced increasingly over time. The rate of subsidence depended on the composition of the underlying alluvium and architecture of the crevasse splay itself. At 'De Bogen' new crevasse splay formation, due to a nearby avulsion, ended the exploitation phase. This event took place by the end of the Middle Bronze Age or in the first half of the Late Bronze Age. The newly formed crevasse splay complexes were used for human exploitation in the Middle Iron Age, as demonstrated by the presence of a burial, an enclosure and several other features associated with human activity (Meijelink and Kranendonk, 2002).

In addition, settlement areas on crevasse splay complexes dating from the Late Iron age (250-12 BC), Roman Period (12 BC – 450 AD) and the Middle Ages (800-1200 AD) were discovered during other excavations carried out in advance of the construction of the Betuweroute (resp. Milojkovic and Smits, 2002; Sier and Koot, 2001; Oudhof *et al.*, 2000). This implies that human occupation on crevasse splay deposits was a common aspect in the Rhine-Meuse delta in both prehistory and history before river embankment.

3.3.3 Other archaeological excavations

Since the Betuweroute-project was undertaken, the possibility of (pre)historic habitation on crevasse splays has become widely accepted among Dutch archaeologists (e.g., Jongste 2001; Arnoldussen,

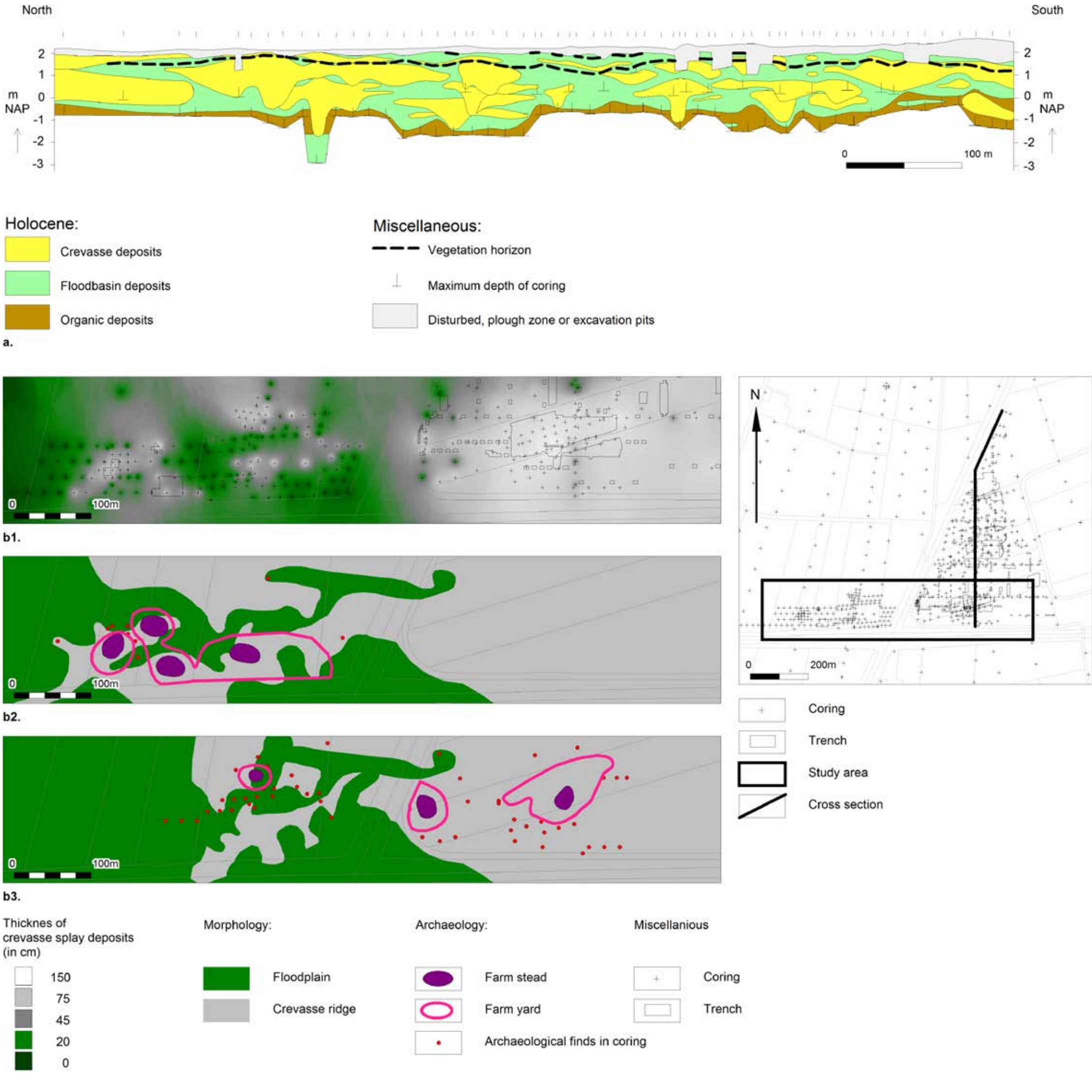

Figure 3.7 Excavation site 'Rumpt – De Bogen', a. cross section of excavation site, b1. thickness of crevasse splay deposits, b2. spatial distribution of crevasse splay deposits in Early Bronze Age and b3. spatial distribution of crevasse splay deposits in Middle Bronze Age.

2008; Arnoldussen and Fokkens, 2008). This has resulted in an increasing number of archaeological sites that were found on crevasse splay deposits (Fig. 3.1; a.o. Maas en Waal – De Ret (Vos, 2003), Geldermalsen – Hondsgemet (van Renswoude and van Kerkhoven, 2009e), Leidsche Rijn – De Balije (Vos and Blom, 2003), Tiel – Medel (Hielkema, 2003; Ufkens, 2004; Heeren, 2005), Elst – Westeraam (Prangsma, 2005), Zaltbommel – de Wildeman (Veldman and Blom, 2010), Druten – Deest aan het water (de Boer *et al.,* 2003), Utrecht – Hoogeweide (Hartog, Mooren and Wynia, 2009), Hazerswoude-Windmolenpark (Diependaele and Drenth, 2010), Geldermalsen-De Plantage (Tops *et al.,* 2006).

3.4 Discussion

Based on the many detailed studies of crevasse splay deposits encountered during archaeological research projects that have been carried out during the last decades, several observations can be made with regard to:

1. The development of crevasses splays during the life-time of an alluvial ridge;
2. The start and kind of exploitation by man;
3. A model for exploitation of crevasse splays during its life-time;
4. The potential of new survey techniques for improving archaeological prospection and preservation policy.

3.4.1 The development of crevasses splays during the life-time of an alluvial ridge

Crevasse splay deposits can form at any stage in the history of an active alluvial ridge. However, we assume, based on observations from several areas in the Rhine-Meuse Delta, that crevasse splay complexes are mainly formed during the mature and final phase of an alluvial ridge. During the initial phase of alluvial ridge development, levees are still relatively low. Therefore, water can flow easily over the levees onto the flood basin during flood stages without creating catastrophic levee breaches. These sediments can be easily recognized as flood basin sediment with a higher $CaCO_3$ content and slightly higher silt content. These sediments are usually not consolidated and lack a vegetation horizon at the top. During the mature phase of the river, channel width and levee height are usually in equilibrium with main river discharge. Crevasse splays will only develop during exceptional, catastrophic peak discharges, and can be recognised as coarser grained sediment bodies within a clayey substratum. During the final phase, as upstream avulsion has occurred, within-channel sedimentation becomes dominant (Makaske *et al.*, 2002). Makaske et al. (2009) conclude that in certain parts of anastomosing rivers bed aggradation may also outpace levee accretion. In both cases, even a modest increase in discharge may cause levees to collapse frequently and crevasse formation will take place extensively.

3.4.2 The start and kind of exploitation by man

If the presumed chronological correlation between the Homoet and Westerveld alluvial ridge is correct, the crevasse splays near Kesteren were inhabited during the final phase of activity of the alluvial ridge. As this occupation probably occurred on newly developed crevasse splays, it also implies that the crevasse splay deposits of phase 3 at this location were formed during the final phase of the alluvial ridge. During this phase, the river discharge already started to decrease and the river became under-fit.

Based on abundant ^{14}C evidence and pottery finds from the sites of Eigenblok, Tiel – Medel, Geldermalsen – Hondsgemet, Wijk bij Duurstede – De Horden and other, we think that most splays became inhabited during the latest phase of alluvial activity or after full avulsion of the alluvial ridge had taken place. However, a few exceptions are known, as for example the Hazerswoude – Windmolenpark and Malburg sites are situated at a fair distance from the formerly active river. It should be mentioned that the first site is probably characterized by repetitive seasonal use and lacks traces of permanent settlement.

The crevasse splay complexes probably gradually lost their relatively high position in the landscape due to ongoing sedimentation in the flood basin. We think that human occupation itself caused increased subsidence. For example, when inhabitants dug ditches, this caused additional drainage and thereby additional subsidence of the splay complex itself into the subsoil. This subsidence occurred probably within a human lifetime: as subsidence exponentialy decreases with time, 80-90% takes place within a decade (Locher and de Bakker, 1990), so likely within human awareness.

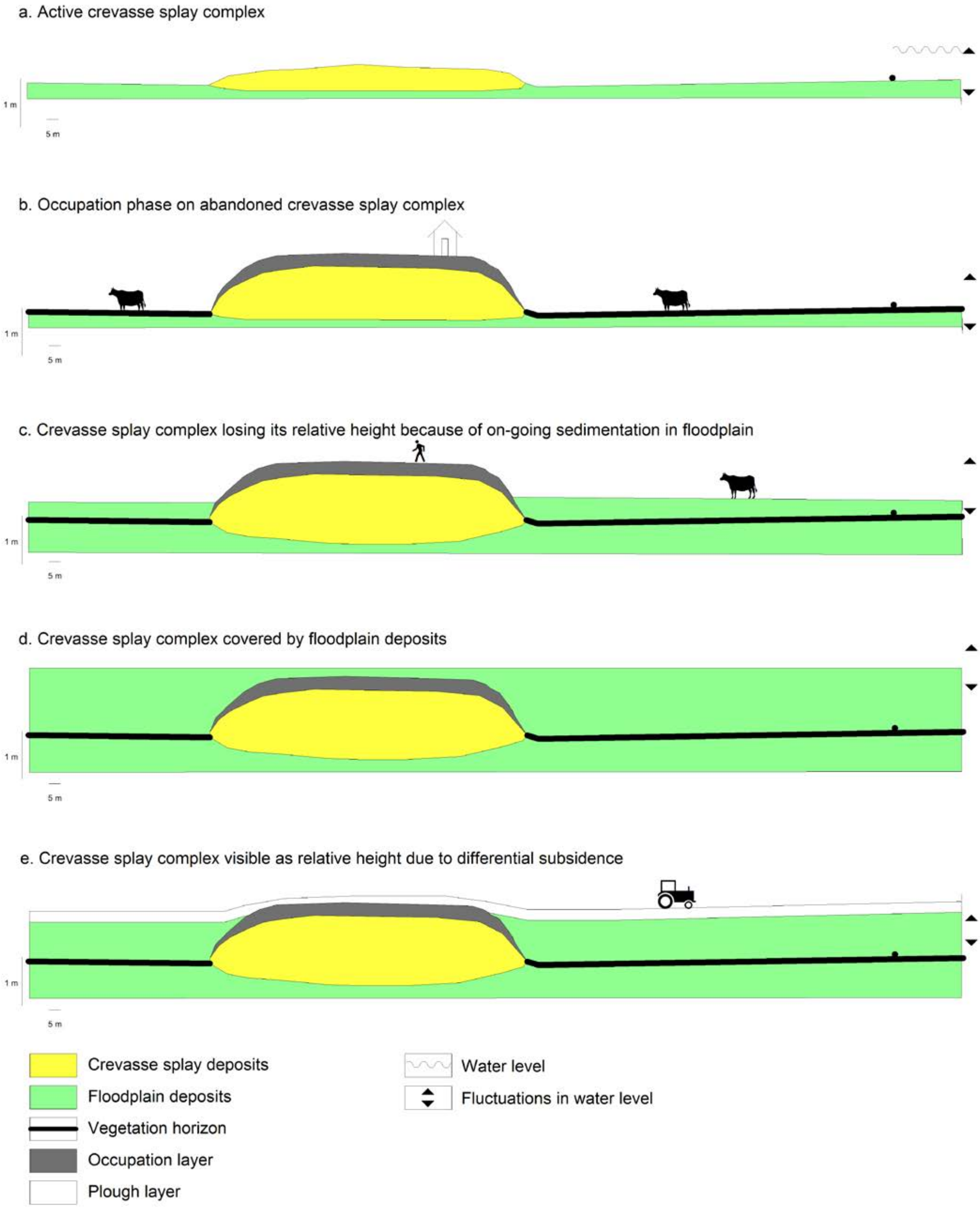

Figure 3.8a-e Schematic evolution of the landscape around crevasse splay deposits.

3.4.3 A model for exploitation of crevasse splays during its life-time

Based on the observations mentioned above, we present a conceptual model for landscape evolution around a crevasse splay (Fig. 3.8). The model also shows when humans were most likely to use this evolving landscape. During the first phase, the crevasse splay complex was formed (Fig. 3.8a). When the crevasse channel silted up, sedimentation on the splay ended and soil formation started in the top of the splay complex (Fig. 3.8b). The splay then became suitable for human occupation. During the Neolithic these locations were probably used for temporary settling, e.g. as spots for fishing or hunting. Man probably took the benefit of the rich wildlife along the natural land-water gradient and the different environments within close range. From the end of the Neolithic onwards, the crevasse splay complexes were in use for agricultural purposes as these areas were fertile, easy to plough, and offered suitable hydrological conditions. Moreover, the adjacent flood basin could be exploited easily. From there, construction wood, especially alder (*Alnus*), and reed could be retrieved and utilized. During the summer, this area was used for herding as well as for hunting and fishing. The nearby river and residual crevasse channel made the locality readily accessible. In time, the crevasse splay complex gradually lost its relatively high position in the landscape, due to subsidence and ongoing sedimentation in the surrounding flood basin (Fig. 3.8c). As a result, the available arable and inhabitable area became smaller, eventually ending occupation, although the area was still suitable for pasturing or agriculture. Finally, the crevasse deposits became completely covered with flood basin deposits (Fig. 3.8d). Between approximately 1200 and 1350 AD, the rivers in the Rhine-Meuse delta became embanked (Lambert, 1985; van de Ven, 1993), which terminated the formation of new crevasse splay deposits. After embankment, differential compaction has caused many older (buried) crevasse splay deposits within the embanked areas to become visible again (Fig. 3.8e)

3.3.4 The potential of new survey techniques for improving archaeological prospection and preservation policy

Although there is increasing awareness that crevasse splay deposits may contain a wealth of well-preserved archaeological sites, consensus towards a standard for the investigation of flood basins in archaeological policy documents is still lacking. In the recently published policy maps, for example the third edition the Dutch Indicative Map of Archaeological Values and the Map for Cultural and Historical Values in the Province of Zuid-Holland (IKAW, https://archis.cultureelerfgoed.nl), flood basins are still mentioned as areas with a low expectation value. Due to differential compaction after river embankment, many crevasse splays partly regained their relatively high positions in the alluvial landscape. Since 2004, detailed height measurements from LIDAR-based images (Laser Imaging Detection and Ranging) have become available. Combined with coring databases (www.dinloket.nl; Berendsen, 2005) and/or available detailed soil maps (scale 1:25.000 or less), these turn out to be excellent tools for tracing and mapping the outlines of many crevasse splay complexes (Fig. 3.9; a.o. Van Zijverden and Laan, 2005; Waldus and Van der Velde, 2005; Berendsen and Volleberg, 2007). Still, these novel techniques remain totally unappreciated in archaeological prediction modelling. In archaeological policy documents, flood basins are still structurally ignored on the basis of the so-called “wet – feet-criterion”, which is the idea that man avoided flood basins for exploitation because of the relatively high water level in these areas. This false idea leads to a structural under-appreciation of flood basins for archaeological investigation, running the risk that crevasse splays deposits farther away from the alluvial ridge and their archaeological sites are missed. This attitude leads to the self-fulfilling prophecy that flood basins do not contain deposits that were suitable for human settlement and therefore lack any traces of exploitation by man.

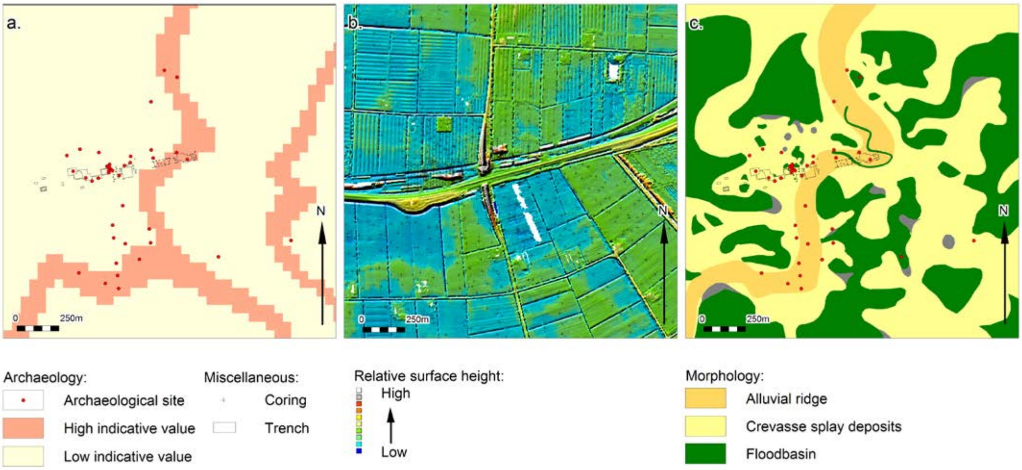

Figure 3.9 Site ' Rumpt - Eigenblok' on a. Archeological Indicative Map (IKAW), b. digital elevation model (DEM), and c. morphological map.

3.5 Conclusion

Recent research in the Rhine-Meuse delta has revealed that young crevasse splay complexes were preferred locations for human settlement within flood basin areas. This implies that human occupation in the Rhine-Meuse delta was more extensive than previously thought. The splays formed relatively high and dry areas of varying sizes for settlement, some so small as to be barely large enough for one farmstead. A thickness of only 20-30 centimetres was enough to raise the complex above the surrounding flood basin and to allow for (temporary) settlement. The nearby alluvial ridge and surrounding splay complex could be used for arable farming. Furthermore, crevasse splay complexes represented important environmental gradients and were ideal for exploiting the adjacent flood basin. The nearby river and water containing residual crevasse channel made the splay localities easy to reach. Usually habitation continued after avulsion had taken place.

Because of subsidence and ongoing sedimentation in the surrounding flood basin, crevasse splay complexes gradually lost their relatively high positions in the landscape. This process may have continued at an accelerated velocity during the period of human occupation, sometimes limiting the duration of occupation. Occupation has been shown to vary from one generation (~ 30 year) for small splays to over thousand years for very large splays.

The first exploitation of crevasse splay deposits can be dated to the Middle Neolithic, 3200-2800 BC. Permanent human occupation of young crevasse splay complexes took place from at least 1400 BC (Middle Bronze Age B) and possibly since the last phase of the Late Neolithic (2450-2000 BP).

Although crevasse splay deposits are nowadays well known for their well-preserved archaeological sites, they are still unappreciated in documents for archaeological policy. Many crevasse splay deposits, and accordingly, archaeological sites on top of them, are not mapped very well or at all. During archaeological investigations in flood basins the "wet feet criterion" is still often used, leading to a lower research intensity or no research at all. The use of a LIDAR data combined with coring databases and/or detailed soil maps should be included in policy documents as a potential research method.

4 Could the local population of the Lower Rhine Delta supply the Roman army?

Part 1: The archaeological and historical framework

Published as: Kooistra, L.I., M. van Dinter, M.K. Dütting, P. van Rijn (†) and C. Cavallo, 2013. Could the local population of the Lower Rhine Delta supply the Roman army? Part 1: The archaeological and historical framework. Journal of Archaeology in the Low Countries 4, 5-23.

4.1 Introduction

In the 40s AD the Roman army built a series of wooden forts and watchtowers in the Rhine delta between Vechten and the North Sea coast (Fig. 4.1). Publications have appeared on the relatively small forts (e.g. Glasbergen, 1972; Haalebos, 1977; Polak *et al.,* 2004; Ozinga *et al.,* 1989) and on the size and composition of the army (Bechert and Willems 1995; De Weert, 2006; Polak, 2009; 2017). We also have information on the reason behind the military installations; in the first century they mainly functioned to protect shipping on the Rhine, and from the end of the first century also to mark the northwestern border of the Roman province *Germania inferior* (Polak *et al.,* 2004, 249-250; Graafstal, 2017).

A sustainable frontier, however, requires a well-organised food supply (e.g. Groenman-van Waateringe, 1989) and limitless supplies of building materials. It is precisely these two important aspects that are relatively little known. The accepted belief is that both a large part of the food as well as that of the wood for construction were imported. The arguments behind this belief are that the carrying capacity of the landscape was insufficient, and that the local population was not used to producing a substantial surplus (Bloemers, 1983; Van Es, 1981, 166-173; Whittaker, 1994). Moreover, there are a number of historical and archaeological indications for the import of food, especially. Tacitus (*Historiae* IV, 26) described how in the first century, forts had to be supplied by cereal ships along the river Rhine. In Nijmegen, an inscription from the 2nd/3rd century AD was found referring to a *Nervian* grain trader (Driessen, 2007) and a ship filled with cereals was found near the fort of Woerden; the ship dates to the last quarter of the 2nd century, and the cereals probably came from the loess area (Pals and Hakbijl, 1992). Furthermore, there is a Late Roman source that mentions grain imports from Great Britain, destined for the Roman army (Mattingly, 2006, 491, 505). The same seems to apply to animal food products for the army. The revolt of the Frisians in AD 28 is famous, and one of the reasons behind the revolt was the size of cattle hides that was demanded by the Romans (Tacitus, *Annales* IV, 72-73). An indirect deduction that has been made from this is that not only the hide but the entire animal was supplied. This is why the model pictured by Bloemers (1983) has been followed for a long time: the Roman army in the Rhine delta was supplied by cereals from the loess zone (northern France, Belgium, Dutch South Limburg and the German Rhineland) and meat from the terpen region (the northern Netherlands and northern Germany). However, this model is due for a revision.

Recent research has demonstrated that, contrary to what people used to believe, the local population around the northwest frontier was fully integrated into the Roman world (e.g. Derks

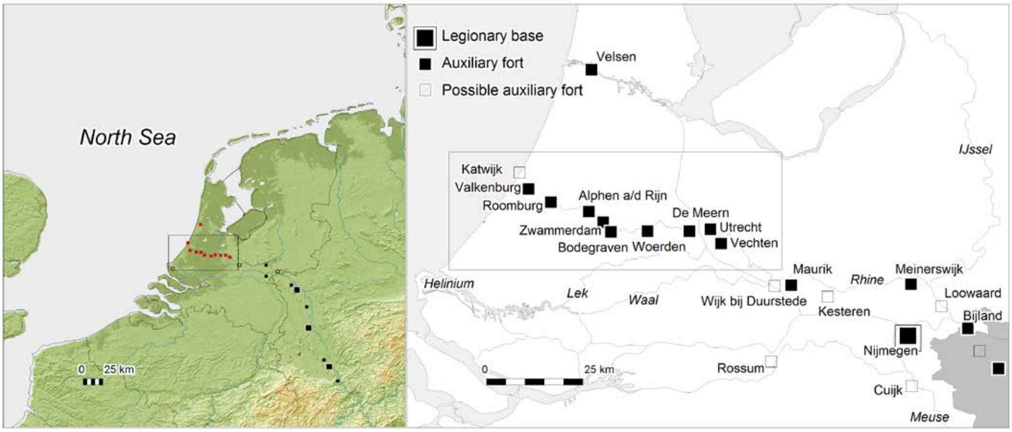

Figure 4.1 Research area in the Netherlands with Rhine delta forts projected on modern topography (after Polak, 2009). Box indicates research area.

and Roymans, 2002; Heeren, 2009; Vos, 2009) and involved in supplying the army with food (Groot, 2008; Groot *et al.,* 2009; Kooistra, 1996; idem, 2012; Vos, 2009). This, despite the fact that the population lived not in villas but in wooden byrehouses (Heeren, 2009; Meffert, 1998; Roymans, 1996; Van Londen, 2006; Vos, 2009; Wesselingh, 2000) in a dynamic landscape with an alternation of dry and wet areas and soils rich and poor in nutrients. In this context, an infrequently used quote from Tacitus in *Germania* (caput 5) is interesting:

'Their country, though somewhat various in appearance, yet generally either bristles with forests or reeks with swamps; it is more rainy on the side of Gaul, bleaker on that of Noricum and Pannonia. It is productive of grain, but unfavourable to fruit-bearing trees; it is rich in flocks and herds, but these are for the most part undersized, and even the cattle have not their usual beauty or noble head. It is number that is chiefly valued; they are in fact the most highly prized, indeed the only riches of the people' (Tacitus, *Germania,* caput 5, http://sourcebooks.fordham.edu/halsall/source/tacitus1.html).

Excavations of military installations and rural settlements in the Rhine delta have produced a wealth of data on food and on wood as a construction material. All these data combined with detailed information on the landscape make it possible to investigate to what extent the local population was involved in supplying the Roman army in the Rhine delta, and what the carrying capacity of the landscape was with regard to food and wood.

The research is based on published and unpublished archaeological, palaeo-ecological and geomorphological data. Information from historical sources and ethnographical research has also been incorporated. The research area covers a zone of five kilometres to the north and to the south of the river Rhine, from a point eight kilometres to the east of the fort at Vechten to the estuary of the Rhine near Katwijk (Fig. 4.1). The results are published in a diptych of articles (Chapter 4 and 5). The current chapter, part 1 of the diptych, analyses the data in a descriptive way. To gain insight into the required amounts of construction and firewood and food for the Roman army and their associates, as well as into the potential scale of the food production by the local population and the carrying capacity of the landscape with regard to food and wood, a conceptual model was developed. The model will be presented in part 2 (Chapter 5), by means of an example of calculations. The combination of descriptive and mathematical archaeology leads to new insights into the supply of food and construction wood – most importantly for the period AD 40 to 140 – to the Roman army in the Rhine delta.

4.2 The Rhine delta in the Roman Period

In recent years, Van Dinter (2013) has analyzed in detail LIDAR-data and geo(archaeo)logical, geomorphological and soil data of the Lower Rhine Delta between Vechten and Katwijk. This has resulted in a palaeogeographical map for the Roman period which covers an area of more than 1,500 km^2 (Fig. 4 2). This research has revealed that the Roman defence system, situated on the southern side of the Lower Rhine, was built in three different types of landscape. Each type has its own possibilities and limitations for living grounds, food production and the occurrence of wood.

The eastern part, with the forts of Vechten, Utrecht and De Meern, the so-called river region, was part of the Dutch River Area. The river Vecht branched off in a northerly direction near the fort at Utrecht. In the Roman period, the Dutch River Area was characterised by active rivers flanked by levees, older alluvial ridges (levees formed by former rivers together with their residual channels) and flood basins (Berendsen, 1982; Berendsen and Stouthamer, 2001). Height differences were minimal in the Dutch River Area and the substratum was soft. The alluvial ridges and the levees of active rivers consisted of relatively fertile sandy to silty, clayey soils. They formed the highest parts of the landscape, which rarely flooded (Fig. 4 3a). When levees and alluvial ridges were not used by man, mixed deciduous woodland developed. The composition of this woodland depended on the flooding frequency (Van Beurden, 2008). The majority of the alluvial ridges and levees were already deforested before the Roman period, because these areas were the most suitable as living grounds and these woodlands delivered the best quality timber. The alluvial ridges and levees were also in use for arable farming and animal husbandry (Groot and Kooistra, 2009). From the relict woodlands timber and wood for fuel could be collected. The flood basins were the lowest areas in the Roman riverine landscape. During every flood, flood waters brought fertile clay into the flood basins. This explains the nature of flood basin soils: fertile but wet and heavy. Water levels varied between different parts of the flood basins, and throughout the year. The highest water levels occurred during winter and in springtime. In a natural situation reed and sedge marshes covered the lower-lying areas. In drier places wetland woodlands occurred in which alder and willow dominated (Groot and Kooistra, 2009; Van Beurden, 2008). Due to the heavy clays and overall wet conditions, the flood basins were not suitable for arable farming, but were perfectly suited for pasture and hay meadows for cattle, sheep and horses. The wetland woodlands could be used to collect timber and wood for fuel.

The central part of the line of defence, with the forts of Woerden, Bodegraven, Zwammerdam and Alphen aan den Rijn, was located on the southern levees of the Lower Rhine, which formed a narrow corridor of accessible terrain through extensive wetlands with active peat development (Chapter 2; Fig. 4 3b). As in the river area, the levees in this peat region consisted of fertile sandy and silty, clayey soils and the low-lying flood basins of fertile, but heavy clays. In a natural situation, the levees were covered with mixed deciduous woodland and parts of the flood basins with wet alder woodlands (Van Rijn, 2009). It is likely that the low-lying parts of the levees and flood basins were covered with reed and sedges. Behind the flood basins Van Dinter (2013) reconstructed extensive eutrophic fen woodlands, mostly consisting of alder carrs. Further away from the river, the fen woodlands gave way to mesotrophic reed and sedge fields, followed by huge, dome-shaped,

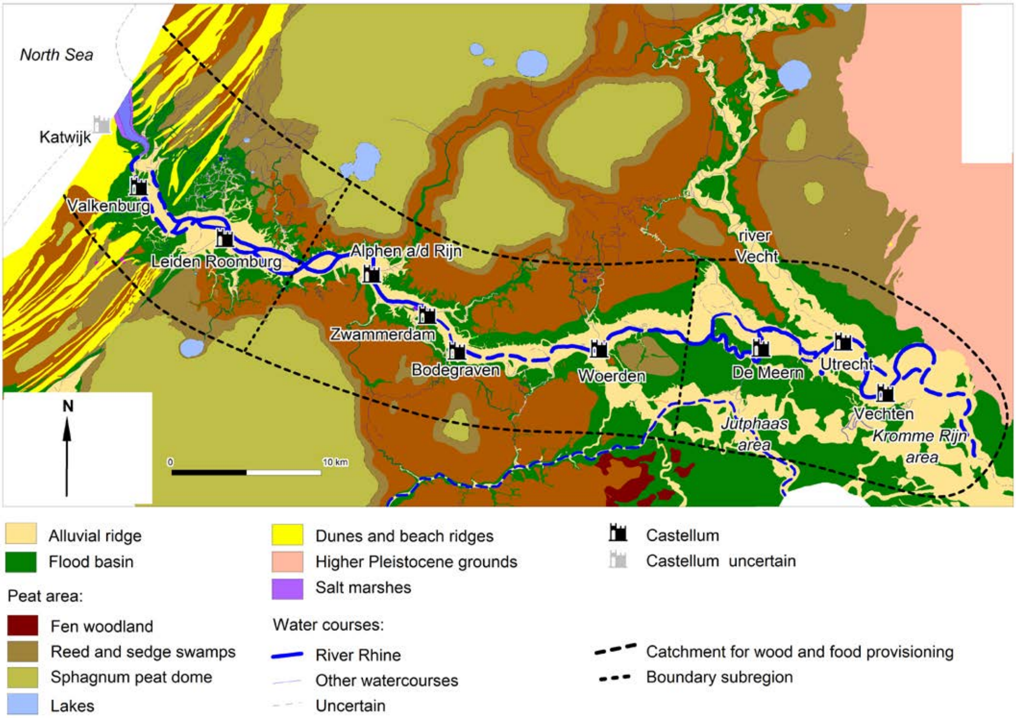

Figure 4.2 Palaeogeographical map of the western Lower Rhine Delta during the Roman period (after Chapter 2).

nutrient-poor *Sphagnum* peat bogs. Although these peat bogs were the highest places in the area (Fig. 4.3b), they were very wet and not accessible. A complex, interconnected network of small watercourses received the drainage water of these domes and transported it to the rivers Rhine and Vecht. The human activities were concentrated on the levees and flood basins in the same way as in the river region. The fen woodlands in the peat area were in use extensively, mainly for obtaining wood, as will be argued below.

The coastal region in the west forms the third type of landscape. The defence system with the forts Leiden-Roomburg, Valkenburg and Katwijk was constructed there. This region includes a freshwater tidal district and the estuary of the Lower Rhine, which interrupted a series of parallel dune ridges and barrier plains (Fig. 4.3c). In the estuary fresh water of the Lower Rhine was mixed with salt seawater. The extent of the reach of salt or brackish water lay just to the east of the fort at Leiden-Roomburg (Chapter 2). The highest places were situated on the levees of the Lower Rhine, with a mix of fertile sandy and clayey soils, and the parallel dune ridges, which consisted of poor aeolian sand. In a natural situation, the dune ridges and the highest parts of the levees were covered with mixed deciduous woodlands of slightly different compositions. The dunes nearest to the sea and the estuary were free of trees, because of salt spray and flooding by brackish water. Various kinds of salt marsh vegetations were found in the flood basins and low-lying parts of the levees in the estuary. Reed and sedge marshes prevailed in the fresh-water tidal district. Peat accumulated in low-lying barrier plains, which existed in between the parallel dune ridges. These peat areas were

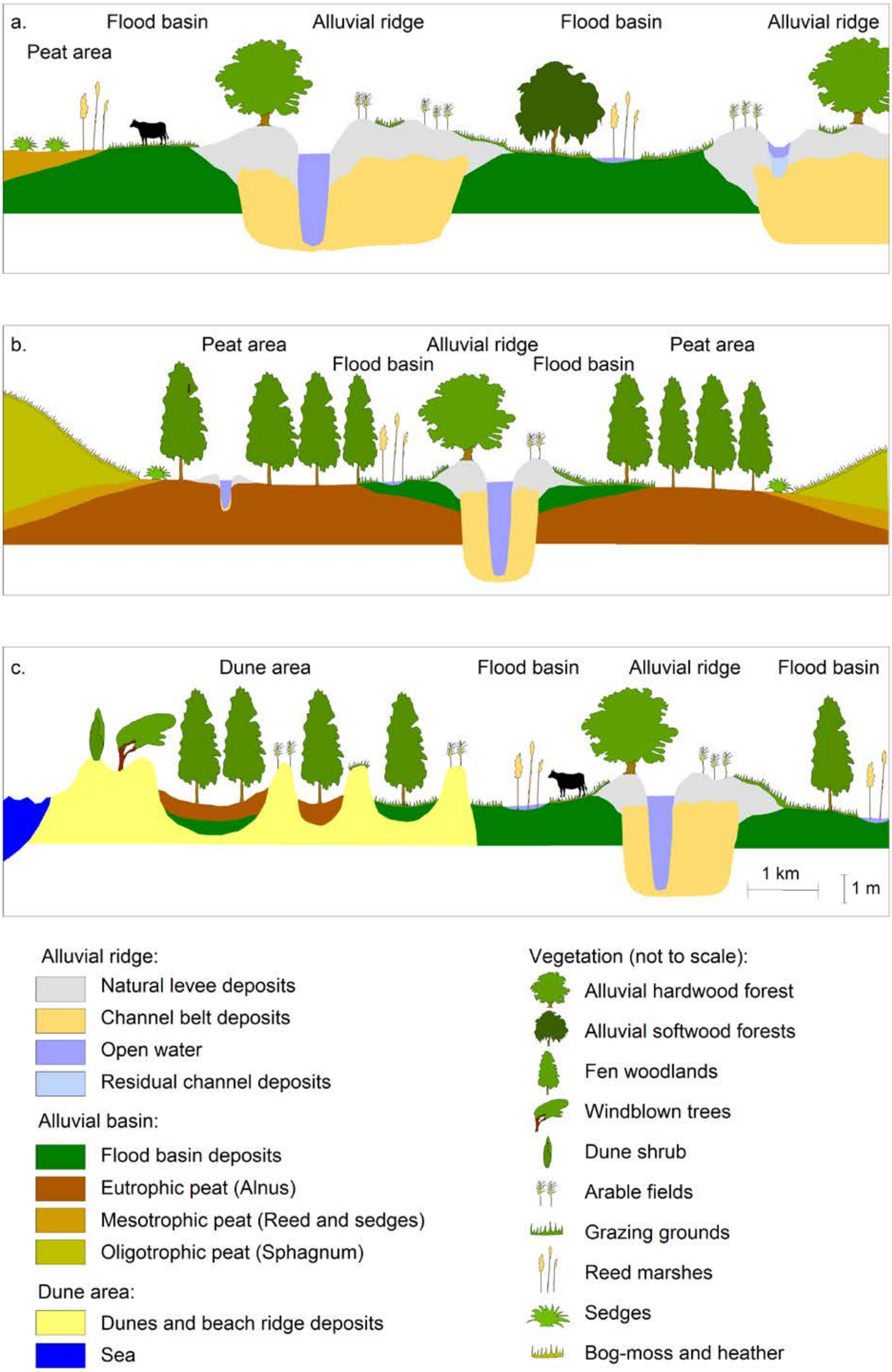

Figure 4.3a-c Cross-sections through the three types of landscape in which the Roman defence system of the Lower Rhine was built, a. river region, b. peat region, c. coastal region.

normally covered with alder carrs (Kooistra, 2008). The land use possibilities were more or less the same as in the other two regions. The dune ridges could have been used for the same activities as the levees and the salt marshes were excellent grazing grounds.

4.3 The Roman army in the Rhine delta

4.3.1 Timber for forts and other military structures

In the first 150 years AD at least seven wooden forts, with sizes between slightly less than one and two hectares, were located in the Rhine delta (Chorus, 2007). Little is known about the fort at Bodegraven, but this fort also seems to have covered circa 1 ha (Van der Kooij *et al.,* 2005). Near Katwijk, a stone construction was located that has been interpreted as a fort, and for which the date is unknown (e.g. Bloemers and De Weerd, 1984; De Weerd, 1986). It is also unknown whether this construction had a wooden predecessor. However, it is likely that a fort was located near the mouth of the estuary in the 1st century (Bosman and De Weerd, 2004; Chapter 2). The fort near Vechten was probably larger than the other wooden forts in the delta. This is the oldest fort of the series and was built in the first decades BC or AD (Polak and Wynia, 1991; Zandstra and Polak, 2012).

The forts are not the Roman army's only structures. Watchtowers were built and quays were constructed. In the late first century, a road was built, partly with a wooden foundation, which connected the forts (Luksen-IJtsma, 2010). Although the building activities did not all take place at the same time, there would have been periods when a large amount of construction wood was required, for instance when the forts and quays were constructed in the 40s AD, after the Batavian revolt in AD 69/70 when many of the forts had burned down, and when roads were built in AD 99/100 and 123/125. In between these moments, construction wood would have been needed for renovations and when regiments changed.

The excavations near and in the forts of Alphen aan den Rijn (Haalebos and Franzen, 2000; Polak *et al.,* 2004) and Valkenburg (Glasbergen, 1972; Glasbergen and Groenman-van Waateringe, 1974; Van Rijn 2004; 2009; 2017) have provided much information on the use of wood in a military context. Moreover, the Roman road has been investigated in various locations, and wood data have become available for other forts and several watchtowers near the fort of De Meern (Langeveld *et al.,* 2010; Van der Kamp, 2007; idem, 2009). On the basis of more than 6000 finds of wood, Van Rijn (209; 2017) has gained insight into the use of wood in military constructions in the Rhine delta and on the origin of the building material.

The research on the wood reveals that a wide spectrum of species was used for the construction of the forts and the accompanying quays between AD 40 and 70. Alder (*Alnus*), ash (*Fraxinus excelsior*) and elm (*Ulmus)* are the most common species. Oak (*Quercus*) and field maple (*Acer campestre*) were used relatively little (Fig. 4.4a). A range of nine species was used for wickerwork, wicker mats and faggots, which adds to the total wood spectrum. The spectrum of used species shows similarities with that of riverine woodland on levees. Because part of the wood that is used in constructions is gnarly and crooked – which would not be the case when it had been imported – it is assumed that construction wood from the local woodland on the levees was used for the layout of the military defence system, perhaps complemented with alder wood from the flood basins and fen woodlands.

The period after circa AD 70 shows a strong increase in the use of alder, while ash, elm and field maple have almost disappeared (Fig. 4.4b). This leads Van Rijn (2004; 2009; 2017) to conclude that the riverine woodland on the levees had become scarce. From the late first century onwards

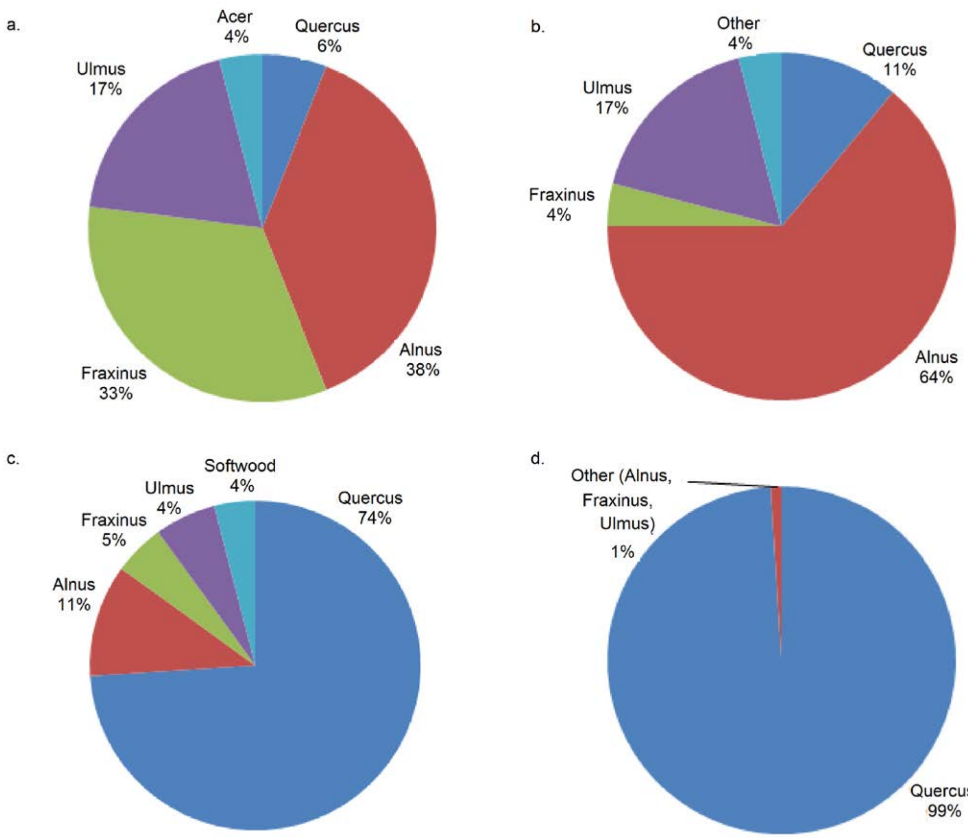

Figure 4.4a-d Relative amounts of wood taxa used for timber by the Roman army in the western Lower Rhine Delta between AD 40 and 140, a. in the forts in the Early Roman period, b. in the forts in the Middle Roman period, c. in the road constructed in AD 99/100, and d. in the road constructed in AD 123/125. Legend: *Acer* = *A. campestre* = field maple; *Alnus* = alder; *Fraxinus* = *F. excelsior* = ash; *Quercus* = oak; *Ulmus* = elm; Softwood = *Abies alba* (silver fir) and *Pinus* (pine).

the construction wood of alder was made out of trees which had more or less the same diameters, and consisted of straight stems without side branches. Van Rijn assumes that this alder wood came from coppiced alder woodlands which were managed by man, and which were probably located on the low-lying parts of the levees, in the flood basins and the fen woodlands. This assumption is extremely interesting, since coppiced woodland provides more suitable construction wood per hectare than natural woodland. The assumption that production woodland occurred in the Rhine delta as early as the late first century indicates that the landscape was at that time already adapted to the increased demand for construction wood.

The selection of oak in the period after AD 70 seems to have been limited to the construction and maintenance of roads and the river infrastructure, especially in AD 99/100 and AD 123/125 (Fig. 4.4c-d). Research into the numbers and pattern of year rings has demonstrated that part of the construction wood came from woodland that had been harvested for wood before.

Wood with several hundreds of year rings also occurs, and some of it has been investigated dendrochronologically. This has revealed that these oaks have come from natural woodland located in what is now the western part of the Netherlands (Visser, 2009; Visser and Jansma, 2009).

Apart from the use in building, wood was the main fuel for various activities, such as domestic use (cooking, baking and heating), craft activities and for cremations. Until now, little was known about the use and origin of firewood in military contexts.

The research on wood reveals that the construction wood for the forts and other military constructions, as well as for the wooden foundations of the road, is mainly of local or regional origin. This result fits with the historical research carried out by Kehne (2007, 324). He writes the following:

'The system of mobilizing material resources to provision the Roman armies in the form of taxes in money and kind was imposed on the new provinces of *Gallia*, *Brittania* and *Germania.* For several reasons the Roman Empire never developed an uniform and universally military supply system. The Roman Empire had to meet logistic needs of the armed forces on a adhoc basis, with a lot of improvisation but constant improvement of the implemented institutions too.'

4.3.2 Timber for *vici* structures

It is likely that a camp village, or *vicus*, was located near each of the forts. Their remains have been found near the forts at Vechten (Vos, 1997), Utrecht (Montforts, 1995), De Meern (Langeveld, forthcoming), Woerden (Blom and Vos, 2007), Zwammerdam (Haalebos, 1977; Ploegaert, 2006), Alphen aan den Rijn (Kok, 1999), Leiden Roomburg (Brandenburgh, 2006; Hazenberg, 2000) and Valkenburg (De Hingh and Vos, 2005; Vos and Lanzing, 2000). However, our knowledge is fragmented, so that we know little about the size and chronology of the *vici.* Most of the *vicus* features, however, date from after circa AD 70 and from the 2nd century AD (e.g. Blom and Vos, 2007, 73, 414; Kemmers, 2008).

Until now, traces of *vici* dating to the early or middle of the first century have only been found near the forts of Vechten and De Meern. A *vicus* seems to have been present at the fort of Vechten from the start (Hessing *et al.,* 1997). The early *vicus* at the fort of De Meern seems to date to the middle of the first century. The structures consist of houses that have been built adjacent to one another, with yards at the back. The houses were inhabited for a maximum of ten years or so, and then abandoned (Langeveld, forthcoming). The absence of first-century *vici* near the other forts may be the result of lack of research or the many disturbances in the soil, which may have wiped out the oldest features. It is also possible that there were no permanent *vici* in the period from AD 40 until the end of the century, when the forts only served to protect shipping, with the exception of the large fort at Vechten (see below). Because only small sections of the *vici* have been excavated, their size is unknown. The inhabited area around the forts is estimated at several to several tens of hectares.

Unlike the forts, nothing is known about the use of wood in the buildings in the *vici* in the Rhine delta. Considering the wood use in the fort constructions, however, it seems likely that the buildings in the *vicus* were also mainly built with local wood. Wood for the early *vici* at De Meern and Vechten may have come from woodland on the alluvial ridges, although botanical research has shown that these were already largely deforested in the Late Iron Age (Groot and Kooistra, 2009). Perhaps this is why alder from woodlands in the flood basins and fen woodlands was widely used in the first century, and oak – being a far better building wood – in a more restricted way.

4.3.3 Military population and their associates

An estimate was made of the size and composition of the Roman army and the associated *vicus* population, in order to gain an impression of the required amount of food. Based on their rather small size, it is assumed that the forts could house one cohors, circa 480 soldiers, but a number of soldiers per fort lower than 480 is likelier (Bechert, 1983; Glasbergen and Groenman-van Waateringe, 1974; Polak *et al.,* 2004). De Weerd (2006) even argues that the forts were only occupied in the first century when it was necessary. The absence of *vici* in this period supports this hypothesis. Graafstal (2017), however, has convincingly argued that the army controlled shipping on the Lower Rhine in this period. That means that the forts must have been occupied at least during the shipping season, from March to October (Fulford, 2000, 42; Vegetius book IV, 39). From the end of the first century, the function of the forts changed, although the size of the forts stayed roughly the same. This makes it likely that the size of the army also stayed the same.

Only the fort at Vechten was almost certainly larger. Indications for this exist especially for the period after AD 70 (Polak and Wynia, 1991; Zandstra and Polak, 2012). It is almost certain that the cohors I *Flavia Hispanorum equitata* (480 infantry plus 120 cavalry) was stationed there. There are some signs that possibly somewhere in the same period cohors II *Brittonum equitata milliaria* (800 infantry plus 240 cavalry) was associated with the fort. After AD 125, the *ala I Thracum* (500 men cavalry) was probably stationed in Vechten for a while. It is interesting to note that the occupation of the fort at Vechten consisted at least partly of cavalry units, because it is generally assumed that most of the forts in the Rhine delta were occupied by infantry units. When we include Katwijk and Bodegraven, there were ten forts between Vechten and Katwijk (Fig. 4.1). Based on an occupation of a maximum of 1 cohors, circa 480 men, per fort and possibly double that number for Vechten, the maximum size of the delta army is estimated around 5000 men.

It is generally assumed that from the late first century onward, it was mainly auxiliary units that were stationed in the forts. The finds of military diplomas indicate that the army units were not local (Polak, 2009; 2017). Less is known about the composition of the army between circa AD 40 and the mid-80s. Tacitus' mention that the Batavians were not allowed to be stationed in their own territory anymore after the revolt in AD 69 has led to the assumption that the auxiliary forts in the Lower Rhine delta were largely manned with local soldiers. However, there is no epigraphic evidence for this, although it is known that a large part of the Batavian and Cananefatian auxiliary units were stationed in Great Britain, for example, in the 40s and 50s (De Weerd, 2006). Taking these considerations into account, it is likely that the size and composition of the army in the period from AD 40 to the mid-80s was similar to that of the following period.

However, there is a large difference in the size of the consuming population till circa AD 70 in comparison with the end of the first century onwards. As has been described above, most *vici,* except those at Vechten and temporarily at De Meern, date after AD 70. The civilian settlements that arose around the forts had a military status and were inhabited by people related to the army (Sommer, 1984; idem, 1991): craftsmen, traders and family members of the soldiers. Although little is known about the size of the population of the *vici* near the forts in the Rhine delta, this is likely to have been similar to that elsewhere in Europe. That means that in later times the number of people living in the *vicus* was more or less equal to that of the garrison in the adjacent fort. The composition of the *vicus* population is a different story. While the people stationed in the forts were mostly men, men as well as women and children lived in the *vici.*

In short, the consuming population in the Lower Rhine Delta from circa AD 40 until the end of the first century probably consisted of around 5000 soldiers and 500 to 1000 civilians, comprising men, women and children. It is possible that the number of consumers nearly doubled in the late first century to around 5000 soldiers and as many *vicus* inhabitants. Considering the presence of cavalry units, especially in Vechten but perhaps also small units in other forts, it is likely that horses, which may have required extra feeding, were kept in the forts.

4.3.4 Food for soldiers and *vicus* inhabitants

Various Roman authors have written about the quantities and the composition of the soldier's diet. In the 2nd century BC, Polybius mentions circa 840 grams (converted) of wheat per day for an infantry soldier, 1.7 kg wheat for an auxiliary cavalry soldier and his servant(s) plus circa 6.3 kg barley for his horse and pack animals (Polybios The Histories 6.39; converted to grams in Erdkamp, 1998, 28). As far as meat is concerned, Polybius writes about special spaces within a Roman camp that were reserved for cattle (Polybios, The Histories 6.31). In the mid-first century BC Caesar wrote that he regularly supplied his soldiers with vegetables and meat, besides cereals (Caesar, De Bello Civilli 3.47; see also the discussion in Erdkamp, 1998, 31-32). Inventory lists for the army from other periods and regions show that the army was supplied with vegetables, fruit and nuts (Davies, 1989, 198-199).

Nevertheless, cereals seem to have been the main part of the soldier's diet in all centuries of the Roman Empire's existence. Under emperor Hadrian, a century and a half after Polybius, a soldier's diet consisted of cereals, bacon, cheese and sour wine (Aelius Spartianus, *Scriptores Histora Augustae Vita Hadriani* 10.2). Vegetius, living in the 4th century, but using sources from earlier centuries, stated that there should be enough supplies of grains, sour wine, wine and salt at all times (Vegetius, De Re Militari 3.3), and when a fort was threatened to be sieged, supplies should be stored within the fort, consisting of enough food for horses and for the soldiers enough cereals, fruit, wine and sour wine. Pigs and other animals should be slaughtered to obtain a good supply of meat (Vegetius, *De Re Militari* 4.7). Olive oil is not named in these sources, although it is likely that this product was part of the basic soldier's diet. A quote from Tacitus is interesting with regard to the necessary amounts of food that should be in store. Tacitus writes that every Roman fort in Great Britain under the governorship of Agricola (between AD 78 and 84) was to have enough supplies for a year (Tacitus, *Agricola* 22.2-3), which amounted to circa 333 kg of cereals per soldier per year (Davies, 1989, 187). Quantities are also mentioned in the Egyptian papyri from the 4th century AD They describe that a soldier had a right to 969 grams of cereals per day (=3 Roman pounds); 646 grams (2 Roman pounds) of meat or bacon, 1.1 litres of wine and 0.07 litres of oil (Garnsey and Saller, 1987, 83-104).

Whether the sources date to the 2nd century BC or the 4th century AD, each soldier had to be supplied with 800 to 1000 grams of cereals a day. Less is known about the quantities of the other required food products. When we consider that 1 kg of cereals provides 3000 to 3300 kCal of energy (Bloemers, 1978; Bakels, 1982), and that an active, young adult man uses between 3000 and 3600 kCal of energy (Den Hartog, 1963, 78-79; Gregg, 1988, 143; Roth, 1999), it becomes clear that cereals were the most important food for the Roman soldier (Kooistra, 2012). This does not deny that meat products, fruits, nuts, vegetables, wine and olive oil were also substantial ingredients of the soldier's diet. Some of the ingredients belonged to the official soldier's diet. In addition, in times of peace soldiers could buy food themselves in the *vici* surrounding the forts. The now famous writing tablets from Vindolanda and other letters reveal that the soldiers also used family and relations to supplement their daily diet (Bowman, 2003).

Analysis of the archaeobotanical and archaeozoological data from military sites in De Meern, Woerden, Zwammerdam, Alphen aan den Rijn, Leiden Roomburg and Valkenburg have given us insight into the food pattern of the military community in the Rhine delta. The archaeozoological research shows that in the start-up phase of a fort, relatively high amounts of pig and chicken were eaten (Cavallo *et al.,* 2008). Once established, cattle became the main meat supplier. This applies to both the 1st and 2nd centuries. Perhaps this can be explained by an insufficiently stable supply of animal products in the establishment phase of a fort. The soldiers would therefore have brought chickens and possibly pigs. Both these animals are fast breeders and require relatively little attention, which means that they could serve as temporary food until the supply lines had been established and the local population could take over (part of) the food production.

The archaeobotanical research (Kooistra, 2009; idem, 2012) shows that until the end of the first century (circa AD 70), there is a broad cereal spectrum in the forts, consisting of bread wheat (*Triticum aestivum*), emmer wheat (*Triticum dicoccon*), barley (*Hordeum*), spelt wheat (*Triticum spelta*), millet (*Panicum miliaceum*) and oat (*Avena*). The weeds found among the cereals indicate that part of the cereals was imported from Gaul. Since bread and spelt wheat are almost absent in agrarian settlements to the north and in the coastal, peat and river area south of the Rhine, it is assumed that these cereals were imported. Apart from remains of cereals, pulses, nuts, fruits and herbs have been found in the forts. Only Celtic beans (*Vici a faba* var. *minor*) could have been supplied by the agrarian settlements in the region. The other listed vegetable food products were not grown in agrarian settlements at this time, and must have been imported. At the end of the first century, the supply of cereals changed. In the forts, only bread wheat, spelt, emmer and barley are now found, with the first two cereals being imported, while the latter two could have been supplied by agrarian settlements in the region. From the 2nd century, some Mediterranean herbs were grown in agrarian settlements to the south of the Rhine. Orchards for fruits and nuts can only be found in the southern and eastern parts of the province of *Germania inferior.* Both in the 1st and 2nd centuries, part of the vegetable food products could have been sourced from the region, and part was imported. How much was imported and how much could have been local cannot be established purely by archaeobotanical research.

The food consumed by *vicus* inhabitants has not yet been discussed. Nothing is known on this topic from historical sources. The *vici* inhabitants were entirely dependent on the forts, since most of the population consisted of traders, craftsmen and relatives of the soldiers. There are no indications from archaeological research that there were any farmers living in the *vici,* growing cereals or breeding livestock. There are some indications for gardens where vegetables and herbs could have been grown (Van Amen and Brinkkemper, 2009). However, it is generally assumed that the *vican*i were food consumers, and that means that they were also mainly dependent on the supply of food by the local agrarian population or on imports over longer distances. The relation between soldiers and vicani was probably so close that most of the *vicus* population would have moved when army units were transferred. This interconnection between soldiers and civilians makes it likely that their dietary habits were similar. This idea is supported by archaeozoological and archaeobotanical research. This has shown that the same food remains are found in the *vici* as in the military contexts (Kooistra, 2009).

4.4 The rural population in the Rhine delta

4.4.1 Settlement distribution

Apart from the carrying capacity of the landscape, the size and composition of the local population determined the amount of food that could have been supplied to the army. The large-scale settlement excavations of recent years have provided a wealth of information on this topic. However, few settlements have been excavated completely and have been studied in enough detail to discover the number of farms per settlement and per period. Vos (2009) made an attempt to collect this information for the Kromme Rijn area, which is located in the northwestern part of the Dutch River area, and was part of the *civitas Batavorum* in the Roman period. The northwestern section of the Kromme Rijn area is part of our research area (Fig. 4 2). Vos uses an average number of 2.5 farms per settlement for the Kromme Rijn area (Vos, 2009, 215), but argues that there is a differentiation in rural settlements in this part of the Batavian region – in between the rivers Rhine and Lek and bordered in the west by coastal peat – varying from many small settlements of one or several households to a few large settlements with a minimum of four farms and a regional function (Vos, 2009, 225-237). It also seems that the number of settlements in this region increased in the first two centuries AD, combined with a developed in settlement structure. Most of the settlements date to the 2nd/3rd century.

Still little is known about the rural population in the peat and coastal regions of the research area, which were probably part of the *civitas Cananefatium.* Only one agrarian settlement, near Katwijk-Zanderij, located in the dunes of the coastal region, has been investigated extensively (Van der Velde, 2008). Van der Velde assumes that the farmers settled there around AD 40, at the same time when the fort of Valkenburg was built nearby. The settlement was abandoned in the 3rd century. During that entire time, the settlement consisted of two contemporaneously inhabited byre houses. The settlement thus seems to have been small, and the population seems to have remained unchanged.

Apart from the excavated settlements, there are numerous observations, obtained from mapping and stray finds. These are stored in the national database ARCHIS (Roorda and Wiemer, 1992; the Archaeological Information System of the Cultural Heritage Agency, RCE). The ARCHIS version, updated to January 2009, has been consulted to obtain an impression of the number of agrarian settlements in the research area from the 1st and early 2nd centuries. This approach has some drawbacks (see also Vos, 2009, 29-30). For instance, most observations are not closely dated, and not every observation represents a rural settlement. Moreover, erosion has caused settlements to disappear in the course of history, and undoubtedly there are also settlements that have not yet been discovered. To estimate the number of rural settlements, observations have only been selected if they comprise multiple finds, if several observations occur within a radius of 200 m, if a cultural layer has been found, and if the observations are located on alluvial ridges, levees and parallel dune ridges. This exercise has yielded 210 possible rural settlements from the Roman period, most of which are located in the river region and the coastal region (Fig. 4.5). The peat region seems to have been sparsely populated.

The question is to what extent the reconstructed number of settlements and the differences in density in the three regions of the research area match the actual situation. It is likely that erosion and sedimentation in the peat region is less or at the most similar to that in the river region. This could lead to the conclusion that the peat region was indeed less densely populated. However, the peat and coastal region have not been mapped in the same intensive and systematic way by field surveys and phosphate mapping. Furthermore, it is likely that the coastal region, where the Roman features may have been covered by the sand of the Young Dunes, harbours more undiscovered settlements than the other two regions.

It is unlikely that all 210 reconstructed settlements existed at the same time. It is generally assumed that the Early Roman period until circa AD 70 was less densely populated, although reality may have been distorted because pottery from that period is not always well recognised (Groot *et al.,* 2009; Heeren, 2009; Vos, 2009). After the creation of the province of *Germania inferior* by

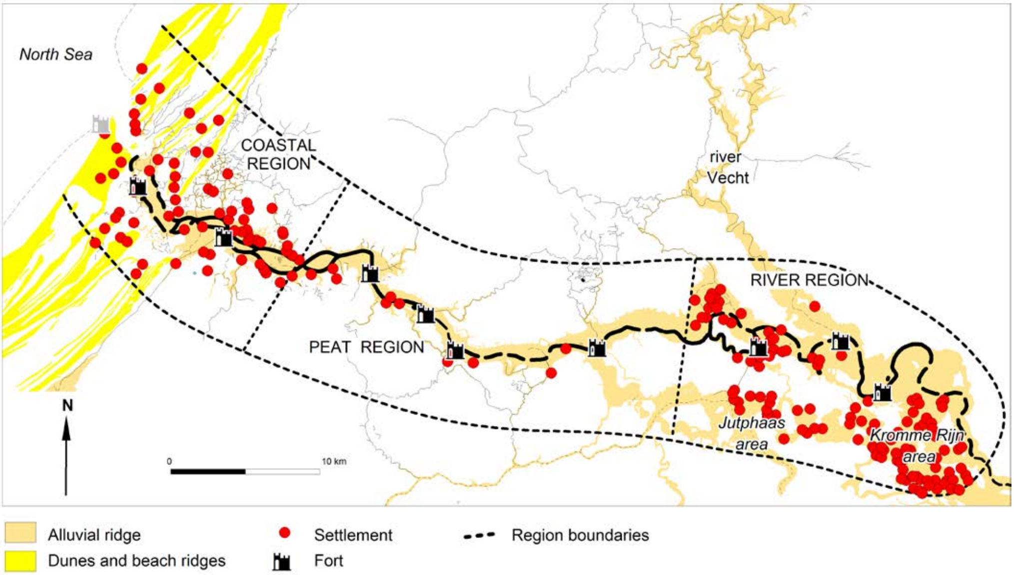

Figure 4.5 Reconstructed settlements in the western Lower Rhine *Limes*- zone based on ARCHIS database (2009).

emperor Domitian, in the 80s AD, the countryside to the south of the Rhine developed quickly and the number of settlements increased (Groot *et al.,* 2009; Vos, 2009; Willems, 1986). The settlement pattern to the north of the Rhine has not yet been investigated on such a large scale or with similar detail. As far as we can tell from the data, the number of settlements there does not appear to increase. It rather appears as if settlements were abandoned in the mid-first century (Den Hartog, 2009) and that new settlements were founded at other locations in the 2nd/3rd centuries (Stronkhorst, 2004).

The rural settlements in the research area in the 1st and 2nd centuries AD consist of wooden constructions. The discoloured features in the soil are the only remains that are left of these buildings, so that no information is available on the wood use and the origin of the wood. When wood is found, it comes from the lining of wells. It is self-evident that the farmers also obtained their wood from their immediate surroundings in the 1st and 2nd centuries, just like the military.

4.4.2 Rural population

The size of the rural population is deducted from the average number of farms per settlement and an average number of people per farm; the so-called settlement model. Based on ethnographic research, a household is assumed to have consisted of five to eight people of different ages and sexes (Bloemers, 1978, 55; Willems, 1986, 236; Vos, 2009, 213). If we follow Vos's assumptions and take an average of 2.5 households per settlement, the agrarian population would have consisted of around 3400 people (210x2.5x(5+8)/2). The actual number will probably have been lower, since it is unknown how many settlements were contemporaneous. The settlements in the peat and coastal region were probably also smaller than those in the river area. It does seem likely that the size of the consuming military population including the *vicani* was at least twice the size of the food-producing rural population. In other words, from the 40s AD onward, every production unit or farming family (=210 x 2.5= 525) would have had to produce food for at least ten soldiers (=(9x500)+(1x>500)) and twenty soldiers and *vicani* (={[(9x500)+(1x>500)]x2}) from the end of the 1st century onward.

4.4.3 Arable farming and animal husbandry

It is generally accepted that farmers in the research area only produced food for their own use before the arrival of the Romans (Kooistra, 1996; Groot *et al.,* 2009). The larger granaries found from the Roman period and the change in composition of the livestock in the Batavian region (but also in the rural settlement Katwijk-Zanderij) suggest that the farmers to the south of the Rhine produced a surplus of agrarian products (Groot, 2008; Groot *et al.,* 2009; Groot and Kooistra, 2009; Kooistra, 2009). Although surplus production is assumed, there is no clear specialisation in arable farming or animal husbandry (Groot and Kooistra, 2009; Kooistra, 2009). The farmers grew barley, emmer wheat, oat and sometimes also millet. It is unclear whether Celtic bean and flax/linseed (*Linum usitatissimum*) were common products. Mediterranean kitchen herbs have been found at several rural settlements from the 2nd and 3rd centuries; they are assumed to have been grown locally (Livarda and Van der Veen, 2008). There are no indications for orchards in the Batavian and Cananefatian regions. The only fruits and nuts of which remains have been found in agrarian settlements could have been collected in the surroundings of the sites (Groot and Kooistra, 2009; Kooistra, 2009).

As far as livestock is concerned, cattle remained the main meat provider in agrarian settlements during the entire Roman period. The cited quote from Tacitus (*Germania*, caput 5) indicates that the local cattle were small in size. The appearance of larger cattle in the Roman period was the result of the improvement of stock-breeding practices to obtain a higher production of beef and/or for traction and other agrarian purposes (Lauwerier, 1988). In the first century, more sheep may have been kept for meat (Groot, 2008). Horses were bred in the Batavian region, probably for the Roman army, but not for their meat (Luff, 1982; Lauwerier, 1988). In the river area, botanical research has provided indications for the location of pastures. Some were located on the alluvial ridges and perhaps on fallow fields, but most botanical finds point to grassland vegetation in marshy areas (Groot *et al.,* 2009; Groot and Kooistra, 2009; Kooistra, 1996; Kooistra and Van Haaster, 2001).

Although the agrarian population to the south of the Rhine was integrated in the Roman Empire to a high degree, hardly any imported food plants have been found in the agrarian settlements. Based on these results, it is assumed that in the Roman period the rural population produced its own food and did not import food from elsewhere. When we consider the agrarian products in the *Limes* -zone, it is likely that, as far as vegetable food is concerned, the rural population produced a surplus of cereals. For animal products, besides breeding horses, the emphasis seems to have been on the improvement of stock-breeding practices in case of cattle, although extra sheep were perhaps bred temporarily.

4.5 Did the local population supply the Roman army?

The dynamic and varied landscape of the *Limes*- zone has undoubtedly influenced the way it was used. Analysis of wood data has demonstrated that wood for the construction of the forts, but also for later building activities, was acquired from the woodland in the *Limes*- zone. Most of the wood used in the construction of the forts around AD 40 came from the woodland on the levees and alluvial ridges. From the second half of the 1st century onward, most of the wood came from wetland woodland in the flood basins and the fen woodlands, where from the late 1st century production woodland was probably located. The bioarchaeological research has provided indications for the surplus production of cereals and the breeding of livestock. The fields for cereals would have been located on the levees of the Rhine, older alluvial ridges and dune ridges. Although the potential area for arable fields is limited, the requirements for wood and cereals do not appear to have been in conflict, because different parts of the landscape were used to obtain these products. Several landscape units could have been used for livestock. The required space for animal husbandry could therefore have conflicted with that for arable farming and forestry, but it is precisely because livestock was not tied to particular types of landscape that the animals could have been grazed in places where the other two space-consuming commodities did not grow, such as in the flood basins and the salt marshes. This would certainly not have been a second best option. Due to the regular flooding, the production of vegetation in the flood basins – the food for livestock – was higher than average.

An analysis of the many archaeological and bioarchaeological data has provided an impression of the layout of the landscape in the Rhine delta and landscape use by the military and rural population. The extensive research has provided information on the wood use by the Roman army and the food consumed by the soldiers and their associates. Most of the timber for military constructions came from local woodland, while part of the food was undoubtedly imported, as indicated by the written sources as well as the bioarchaeological research. There are also (bio) archaeological data and several written sources that indicate local food production for the army. It is unclear how important this local food production was. The next contribution will discuss this topic, on the basis of a theoretical calculation model.

5 Could the local population of the Lower Rhine Delta supply the Roman army?

Part 2: Modelling the carrying capacity using archaeological, palaeo-ecological and geomorphological data

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Note: with small corrections in calculation figures (in 5.3.3.1. and 5.3.4.1) and in 5.4.1.

5.1 Introduction

As a result of a number of recent studies on Roman forts and other military structures in the Rhine delta, the development of the Roman frontier is once again at the centre of attention after a period of relative silence (e.g. Blom and Vos, 2008; Luksen-IJtsma, 2010; Polak *et al.,* 2004; Polak, 2009; Van der Kamp, 2007; idem, 2009; Graafstal, 2017). The series of small military forts which were built from the 40s AD onwards between Vechten and the North Sea was in use well into the 3rd century (Fig. 5.1). The original wooden forts were rebuilt in wood several times, for instance after the Batavian revolt (AD 69). It was not until the mid-2nd century that they were replaced by (partly) stone forts (e.g. Bechert, 1983, 94; Blom and Vos, 2008, 416; Glasbergen, 1972; Haalebos, 1977; Ozinga *et al.,* 1989; Polak *et al.,* 2004). It is not only unusual that the forts were rebuilt at the same locations; they were also given a different function at the end of the 1st century. Initially, they served to protect shipping, but when the Rhine became the northwestern frontier of the Roman Empire, the so-called *Limes*, the function changed to border defence (Polak *et al.,* 2004, 249-250; Graafstal, 2017; Chapter 2).

As has already been mentioned in the first part of this diptych (Chapter 4), good logistics and supply are key to the success of military operations (e.g. Groenman-van Waateringe, 1989). These aspects probably also formed the basis of the sustainable stay of the Roman army in the Dutch Rhine-Meuse delta, which lasted several centuries. Of course, the Rhine as a transport river by itself was enough to guarantee the successful presence of the Roman army. However, the question is to what extent the *Limes* landscape and the rural population contributed to the success by supplying the army with food and wood.

In the previous century, based on the then still limited set of (bio)archaeological data, researchers believed that the food for the army in the Rhine-Meuse delta was imported: cereals from Gallia and the meat from Barbaricum (Bloemers, 1983; Groenman-Van Waateringe, 1977; Van Es, 1981, 166-173; Willems, 1986; Whittaker, 1994). At that moment little was known about the origin of the timber for forts and other military structures and the firewood (Groenman-Van Waateringe, 1988; Stuijts, 1988; Van Enckevort, 1987; Van Rijn, 1990).

Chapter 4 is part 1 of this diptych of articles and gives a descriptive overview of the results of archaeological, palaeo-environmental and geomorphological research that has since been carried

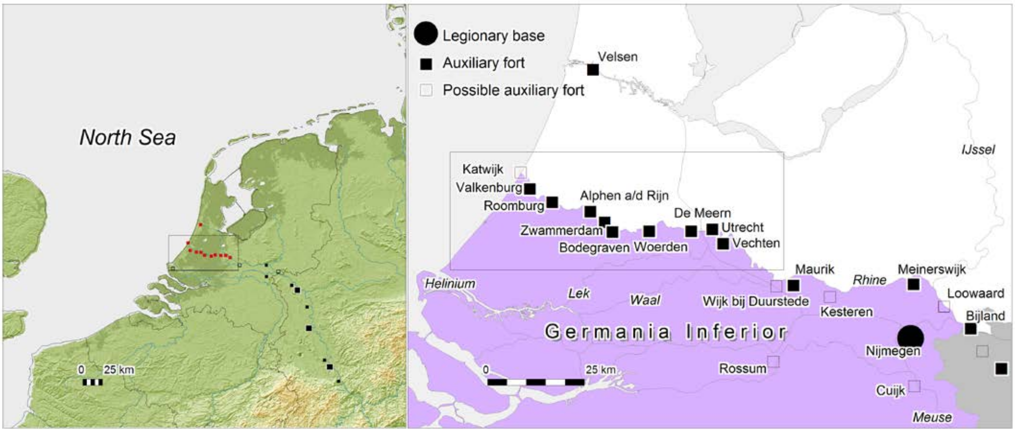

Figure 5.1 Research area in the Netherlands with Rhine delta forts projected on modern topography (after Polak, 2009). Box indicates research area and in purple the Roman province *Germania Inferior* at the end of the 1st century AD.

out in the Rhine-Meuse delta (Chapter 4). This overview reveals that the local population of the central Dutch River Area to the south of the Rhine was completely integrated in the Roman Empire as early as the 1st century. From the end of the 1st century, this population was certainly capable of producing a surplus of crops, mainly emmer wheat and barley, and livestock, mainly cattle (e.g. Groot, 2008; Groot *et al.,* 2009; Heeren, 2009; Roymans, 2004; Vos, 2009). Although not as well researched, this also appears to have been the case for the western Rhine-Meuse delta (Bloemers, 1978; Flamman and Goossens, 2006; Siemons and Lanzing, 2009; Van der Velde, 2008). Timber for military constructions was mainly provisioned from the surroundings of the forts (Van Rijn, 2004; Lange, 2007), except in the case of the large construction campaigns in AD 99/100 and 123/125 during which the road and river infrastructure along the Rhine were drastically renewed (Luksen-IJtsma, 2010, 95). Import products were also found in the forts. For example, the cereals spelt wheat and bread wheat were imported, and it cannot be excluded that meat was also imported. The amphorae present in the forts make clear that more products were imported, such as wine, olive oil and fish sauce.

The extent of the local production of food for the army, however, cannot be analysed through descriptive, qualitative research. Therefore, in this chapter (part 2 of the diptych) an attempt will be made to establish the extent of the possible local supplies of food and wood to the army in the western Lower Rhine Delta. To this end, a conceptual model was developed in which the landscape and its use are central (Fig. 5.2). This conceptual model is based on an existing landscape model (Kooistra, 1996, 63-80; 92-113), with the addition of more recent site models (Groot *et al.,* 2009; Groot and Kooistra, 2009; Vos, 2009). In the models of these authors, the landscape and its use by the agrarian population were central. The conceptual model presented here is more extensive because it also contains the requirements of the Roman army for food and wood.

Subsequently, this conceptual model is applied to the western Lower Rhine Delta for the first 100 years following the arrival of the Roman army to estimate the demands and supplies of wood and food. Accordingly, these quantities are converted into areas of land necessary to produce the quantities needed. Based on these estimated amounts the following questions will be answered: 1.

Could the provisioning theoretically have been sustained by the local environment? And if so, 2. Could the local rural population hypothetically have produced enough surplus to fulfil the demand of the army? The results of the calculations are also compared to the archaeological evidence described in part one of this diptych.

In this way, the calculations will give an indication whether the carrying capacity of the area was significant or not and contribute to the discussion on the role of the local population in the provisioning of the Roman army and its associates. Therefore, the research offers a unique opportunity to gain further insight into both the carrying capacity of the landscape and the local supply and demand of wood and food in the Lower Rhine Delta after the arrival of the Roman army.

5.2 Methods

5.2.1 Model concept

For this research we developed a conceptual model to determine the potential of the Lower Rhine landscape in provisioning the Roman army with food and wood (Fig. 5.2). This model is based on three main components: (i) the landscape, (ii) the rural population and (iii) the Roman army and its associates. The area of land available for obtaining wood for timber and fuel, and food production in an area forms the central component of the model. A landscape is a defined area within which the geomorphology, hydrology and (natural) vegetation determine the suitability for human activities, by providing wood, and allowing for arable farming and animal husbandry. This landscape thus poses an upper limit on the ***availability*** of local resources.

The rural population forms the second component in the model. The rural settlements in the delta are ***producers*** with an agrarian system based on mixed farming. The rural settlements need wood for timber as well as for fuel. This wood was predominantly locally acquired and probably retrieved from different types of woodland that were present in the surroundings. These various woodlands provided different yields, thereby determining the required area of woodlands. The food production consisted of a mixture of vegetable and animal food. The yields of the fields determine the area of arable land needed, and the animal species and herd size determine the areas of grassland and meadows needed for grazing and fodder. If a surplus of both manpower and suitable land is available, the rural population is to a certain extent able to produce extra food for consumers, like the Roman army.

The Roman army and its associates, such as relatives of the soldiers, craftsmen and merchants, living in the *vici,* form the third component in the model. They only produce food on a limited level, e.g. in gardens, and are therefore considered as ***consumers*** of food. Their food is mainly provided by the surplus produced by the rural population, complemented by food imported from outside the area. When considering wood, they are not just consumers: in our model the Roman army collects wood required for building and fuel by itself in the area. Still, some wood might have been imported from elsewhere. Locally derived wood would have put an extra claim on the woodlands in the area.

5.2.2 Model implementation

We applied the model to the *Limes*- zone in the Lower Rhine Delta in the period AD 40-140. Settlements were located on the alluvial ridges of the Lower Rhine, while the gathering of wood and production of cereals and animal food in the research area is assumed to be basically restricted to a c.10 km wide zone distributed evenly on both sides of the river (Fig. 5.3; Vos, 2009, 230). The eastern border is positioned halfway between the Roman fort at Vechten and the presumed fort

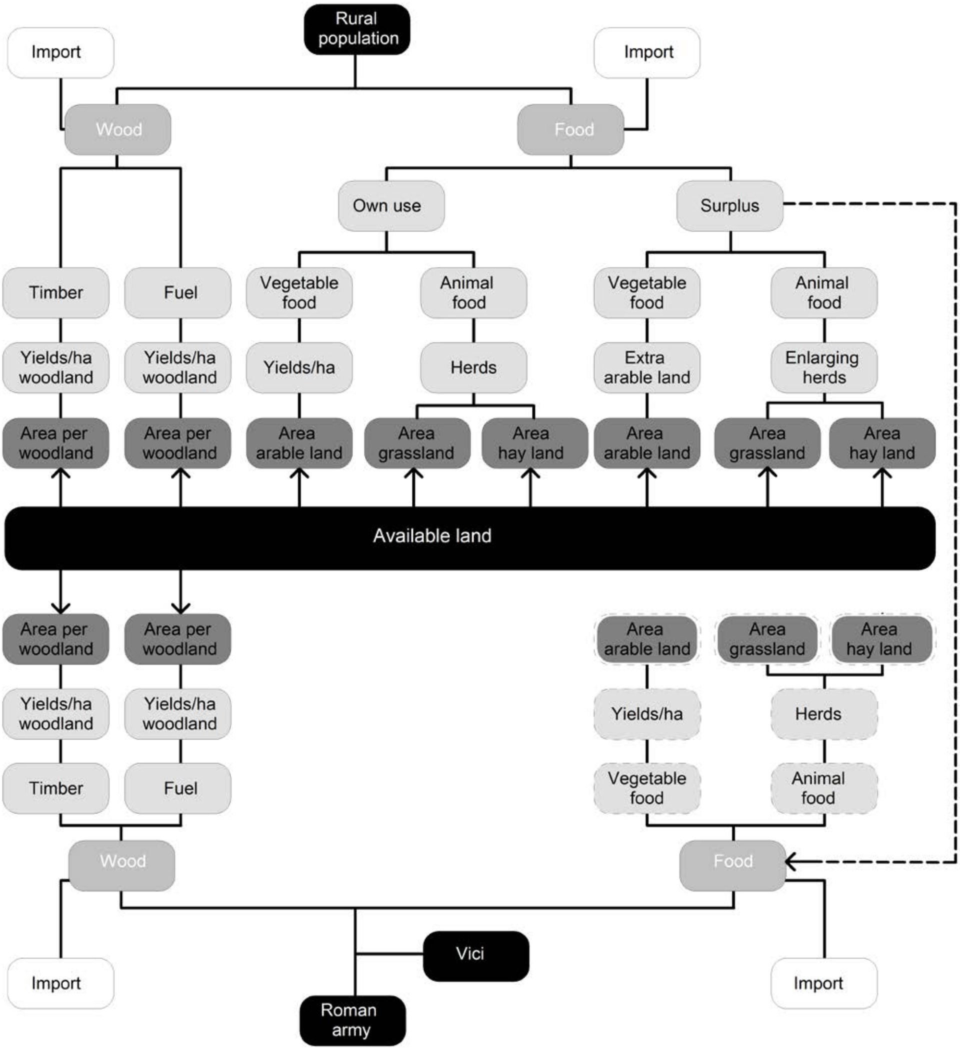

Figure 5.2 Conceptual model of the landscape services in provisioning wood and food, and the demands of the rural population and the Roman army and its associates in the Rhine-Meuse delta.

near Wijk bij Duurstede, e.g. about eight kilometres east of Vechten, and the North Sea forms the western border. The study period is limited chronologically to the period from AD 40 to 140, the time by which a highly complex defence system had been established in the Lower Rhine Delta. As the population size distinctly changes around 70 AD, we distinguish an Early Roman period (AD 40-69) and a Middle Roman period (AD 70-140).

To quantify the carrying capacity of the landscape, and the demand and supply of wood and food in the research area we formulated four modules, i) a landscape module to determine the area of land that was available, ii) a population module to reconstruct the population size, iii) a

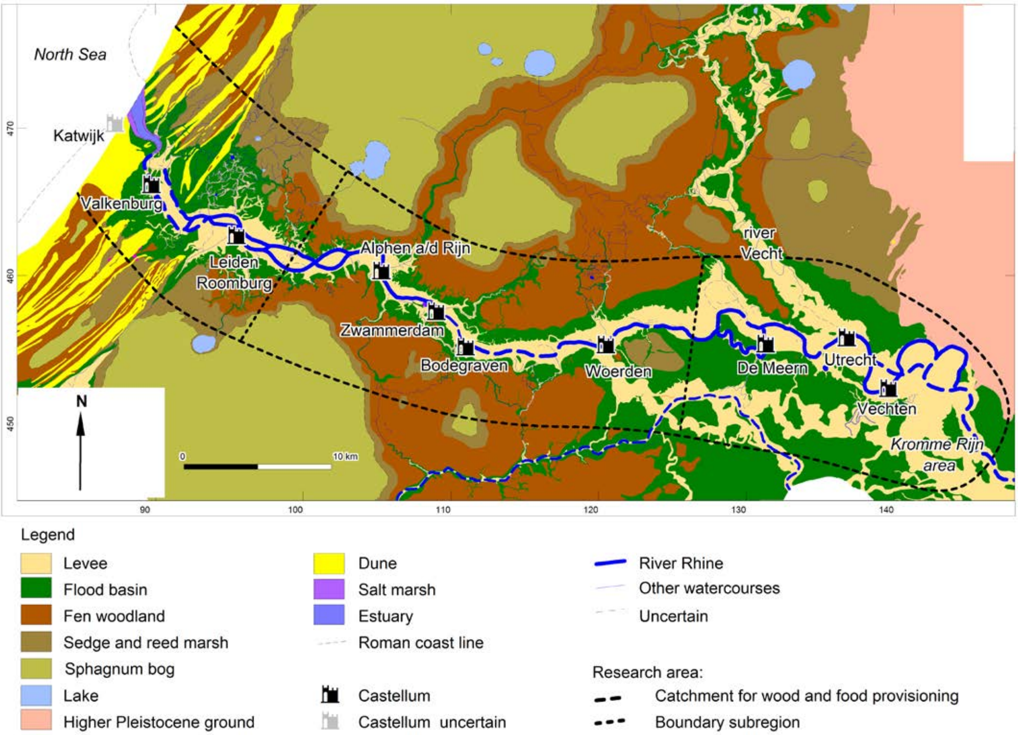

Figure 5.3 Palaeogeographical map of the western Lower Rhine Delta during the Roman period (after Chapter 2).

military module to determine the demand of the Roman army and its associates and iv) a rural module to calculate both the demand and the surplus production capacity of the rural settlements. The data required for these modules are based on a geomorphological landscape reconstruction of the research area (Fig. 5.3) combined with (bio)archaeological data from excavations of military sites and rural settlements. Information concerning the required amount of food for the soldiers, other males, women and children, arable systems, viable herds, yields etc. are obtained from historical sources, ethnographical studies or experiments. The complete list of parameter values and underlying assumptions used in our model is given in Appendix C.

5.2.2.1 Landscape module

The Roman defence system was erected along the south bank of the Lower Rhine (Fig. 5.3). The research area was divided into three different regions, each with their own specific type of landscape (Chapter 4). The river region in the east with several alluvial ridges with broad levees that enclosed clayey flood basins; the central peat region with large peat areas behind the relatively narrow levees and flood basins of the Rhine; and the western coastal region with the freshwater tidal district, the estuary of the Rhine and the dune area. The various geomorphological units have distinct characteristics in terms of elevation and composition of the subsoil and thereby determined the suitability of the area for settlement, woodland growth, agrarian use and animal husbandry (Table

Table 5.1 The different landscape units and their potential for human use (colour = possible suitable; partially coloured means only parts of the landscape unit are suitable); * = only in use as hay land, ** = only in use as grassland, *** = only areas directly bordering a flood basin are in use as hay land.

	Military structures & rural settlements	Wood felling and management	Arable farming	Animal husbandry
Dune				
Levee, high				
Levee, low				
Flood basin, high				
Flood basin, low				*
Fen woodland				
Salt marsh				**
Sedge and reed marsh				***
Sphagnum bog				

5.1). The areas of land (in km^2) that were potentially available in each region for local wood and food supply were determined on the basis of a newly constructed, detailed palaeogeomorphological map (Chapter 2 – Appendix A). In this detailed map the legend units 'levee' and 'flood basin' are subdivided into sub-classes according to their height. The subdivision between 'high' and 'low' in Table 5.1 are based on this subdivision. The distribution of the levees and flood basins east of fort Vechten, the Kromme Rijn area, are based on Berendsen (1982) and the subdivisions into 'high' and 'low' are set at 2/3 respectively 1/3 of the total unit 'levee' and conversely for the 'flood basin'.

5.2.2.2 Population module

The population module estimates the size of both the military and rural populations. The military component in the model focuses on the supply of a *standing* army and includes soldiers stationed in the forts as well as the related inhabitants of the civil settlements, the *vici*, that over time were erected around the forts. Although the forts downstream of Vechten were built to house one cohort, about 480-500 soldiers, writing-tablets excavated in the Roman fort Vindolanda in England show that a fort is often not fully manned (Bowman, 2003, tablet *Vindolanda* II 154; also http://vindolanda.csad.ox.ac.uk). It appears that several of the western Dutch forts did not contain complete cohorts either. Glasbergen and Groenman-van Waateringe (1974) assume that cavalry was also stationed in fort Valkenburg in the pre-Flavian period (AD 40-69; phase 1 two *turmae* and in phase 1b and 2/3 both eight *turmae,* half an *ala quingenaria*). As a result, only 384 respectively 256 men could reside in the fort. Indications for the presence of cavalry are also established for the forts in Vechten and in Utrecht (Zandstra and Polak, 2012; Chorus, 2013). As this evidence is only recently revealed and the other forts do not show evidence for the presence of cavalry, it is not included in our model. But in section 5.4.3 we shortly discuss the amount of food needed for the cavalry horses for these three forts and the possibility for local production.

In our calculations we therefore use a number of 350 permanent inhabitants per fort, and assume a double garrison in the larger fort of Vechten (Appendix C). The extra pressure brought by the provisioning of marching armies, like the gathering of soldiers preceding the British invasion, is not included in our model as these demands are short-termed (Groenman-van Waateringe, 1989). Neither taken into account is the presence of the Roman fleet, because there is no firm evidence (yet) for the presence of large scale military harbours, like in Velsen (Morel, 1988; Bosman, 1997), in this part of the delta during the research period.

Estimates of the rural population size were derived from the reconstructed number of rural settlements in the research area. We attempted to derive a minimum population size, in order to determine to what extent the surplus production by the rural population could meet the needs of the Roman army.

5.2.2.3 Military demand module

The military demand of wood and food was estimated in terms of wood volumes and kCal food. We assume that the army was involved in the felling of woodlands to obtain timber for construction of the various military structures and for fuel. The wood demand comprises the necessary volumes of both timber needed for the military structures (forts, watch towers, roads, waterfront installations, and granaries, all including renovation and repair) and firewood. The presence of bathhouses in the research area has not been established before AD 150. Therefore, the wood consumption regarding their construction and fuel consumption has not been taken into account (Vollgraff and Van Hoorn, 1941; Haalebos, 1977, 65; Polak *et al.,* 2004, 20). Firewood was needed for various activities, such as domestic use (cooking, baking and heating), craft activities and for cremations. Part of this firewood was branch wood or picked up, but most likely this was not enough to cover the demand.

Wood for timber has requirements with regard to tree species and size, but is only needed in large quantities during building campaigns or for large-scale maintenance activities. Fuel wood requires a constant supply, but has less demands in terms of tree species and size. These differences have been considered in the model, as well as the rate at which the forests regenerated after cutting (Appendix C).

We assume that the soldiers and *vicus* inhabitants were only food consumers and not producers (Chapter 4). Estimates of the necessary amount of food of both soldiers and vici inhabitants are based on the diet (in kCal), and the ratio in their diets between plant and animal food. Based on palaeo-ecological and archaeological data it is assumed that the Roman soldiers and their associates acquired most of their energetic requirements from cereals and beef (Chapter 4). In this publication, therefore, the calculations are limited to the demand and supply of cereals that could be grown and supplied locally. We assume that the cereals that could not be grown in the rural settlements in the delta due to specific ecological requirements were imported and these are not incorporated in the model (Appendix C). For meat and meat products, we have accordingly assumed the sole use of cattle in our model.

The next step consisted of the translation of the required m^3 and kCal into areas of woodland, arable fields and grazing grounds (km^2). According to the range of wood taxa in the archaeological record, the wood would have come from various types of woodlands that grew on the different landscape units. The yields of these various woodlands will have differed. The calculations of the areas of woodland are based on estimated wood yields of the woodlands that were used in the Roman period, natural as well as managed ones, that were present in the various landscape units, and divided over the most likely landscape units.

It was not possible to use the yields of modern natural woodlands in the Netherlands for the estimation of the yields of the natural woodlands (Clerckx *et al.,* 1994; Jansen *et al.,* 1996; Wolf, 1995). First of all because that kind of woodland no longer exists today, and secondly because modern woodlands are relatively young, the substrate is generally moderately nutrient-rich and the hydrological situation is not natural in most cases. Estimates for the yield of the Roman woodlands have therefore been based on research on the remnants of a Roman woodland near Zwolle (M.J. Kooistra *et al.,* 2006; Sass-Klaassen and Hanraets, 2006), and the trunk diameters in combination with the number of year rings of construction wood used in the Roman forts of Valkenburg and Alphen aan den Rijn.

The calculations for the areas of arable fields are based on the energy yield in kCal per kg cereals, the amount of sowing seed, the yields per ha, the rotation system and any reserves. The calculations for meat, however, cannot be based directly on the number of kCal and their equivalent in terms of numbers of animals. The reason is that the slaughtered animals, in our case cattle, are part of a herd. These herds are not slaughtered all at once, but should provide a long-term, steady supply of meat, with other words, the herds have to be large enough to be and stay viable. Therefore, we have chosen an approach in which the number and size of the herds are central, and in which the yield in kCal per herd per year is estimated. Based on the requirement for meat, expressed in kCal, the number of herds necessary is calculated. The number of ha required for pasture and meadows is calculated per herd. The fact that the age composition of the herd and thus its food intake changes throughout the year as a result of births, growth, deaths and slaughter is taken into account. The yield of pasture and meadows is estimated. Through a combination of these data, it was eventually possible to calculate the total amount of pasture and meadows required. We have used optimum and constant yields to estimate the minimum of land needed to sustain the total population in the research area with wood and food.

5.2.2.4 Rural production module

The demand for wood and food by the rural population is likewise estimated in terms of m^3 wood and kCal food and calculated in a similar way to the military demand. From the archaeological record it is clear that the import of both wood, for example wine barrels, and food was very limited and therefore this is not taken into consideration in our calculations. With regard to wood, estimates were made of the required volumes of construction wood for rural farm houses and firewood (in terms of m^3), and with the estimated yields of the woodlands (section 5.2.2.3; m^3/ha) the volumes have been translated into the required areas (km^2).

On the basis of the palaeo-ecological and archaeological data it is assumed that the rural population, just like the military population, obtained most of their energetic needs from cereals and beef (Chapter 4). The estimates for the required amount of food (in terms of kCal) have then been calculated in the same way as in the military module.

Table 5.2: Size of geomorphological units in the western Lower Rhine Delta in the Roman period (in km^2); * = on barrier plain, ** = bordering flood basin.

	West		Central		East	
	Total	South	Total	South	Total	South
Levee, high	17	11	39	22	105	73
Levee, low	16	9	18	10	27	19
Flood basin, high	22	12	18	10	34	24
Flood basin, low	43	17	50	27	75	45
Fen woodland (*)	44 (17*)	22 (5*)	140	77	8	0
Sedge and reed marsh (**)	40 (30)	15 (7)	20 (6)	15 (6)	8 (8)	0
Sphagnum bog	11	4	39	25	0	0
Dune	> 36	> 18	0	0	0	0
Salt marsh	> 2	> 1	0	0	0	0
Total	> 231	> 109	324	186	257	161

Furthermore, the potential surplus production capacity of the arable farming and the animal husbandry was calculated based on surplus labour capacity of the rural population. Subsequently, the total rural demand and supply of food are converted into areas of land (km^2) necessary to produce these amounts.

5.2.3 Local provisioning? Comparisons between carrying capacity, demand and supply

Finally, we compared the area of land that was *available* with the amount of land that was *required* to provide the total population, e.g. the local farmers as well as the Roman army and its associates, with wood and food. Furthermore, we also considered to what extent the local labour capacity was sufficient to carry out the work involved to produce the amount of food that was needed to provision the Roman army with local products.

5.3 Results

5.3.1 Land availability

The landscape of the research area contained a variety of units suitable for different uses (Fig. 5.3 and Table 5.1). The distribution and dimension of these units differs per region (Table 5.2). Table 5.2 shows the size of the various geomorphological units in the three distinguished regions in the research area. The area of high grounds, such as levees and dunes, as well as the area of wet flood basin roughly decreases from east to west. Furthermore, vast fen woodlands were present behind the flood basin in the central and western part of the research area. In the eastern river region, fen woodlands were only present north of the Rhine, downstream along the river Vecht (Fig. 5.3).

5.3.2 Population size

5.3.2.1 Military population

Based on the assumptions listed in Appendix C, the ten forts were populated by a total number of 3,850 soldiers in both periods (Table 5.3; Appendix C). The minimum number of reconstructed vici inhabitants changed from only 700 *vicus* inhabitants in the Early Roman period (around the fort at Vechten) to 3,850 in the Middle Roman period (Table 5.3). This means that the lowest estimate of

Table 5.3 The estimated number of soldiers and *vici* inhabitants per period per region.

	West	Central	East	Total
Early Roman Period (AD 40-69)				
Forts (N)	3	4	3	10
Vici (N)	0	0	1	1
Number of soldiers	1050	1400	1400	3850
Number of vici inhabitants	0	0	700	700
Total population	*1050*	*1400*	*2100*	***4550***
Middle Roman Period (AD 70-140)				
Forts (N)	3	4	3	10
Vici (N)	3	4	3	10
Number of soldiers	1050	1400	1400	3850
Number of vici inhabitants	1050	1400	1400	3850
Total population	*2100*	*2800*	*2800*	***7700***

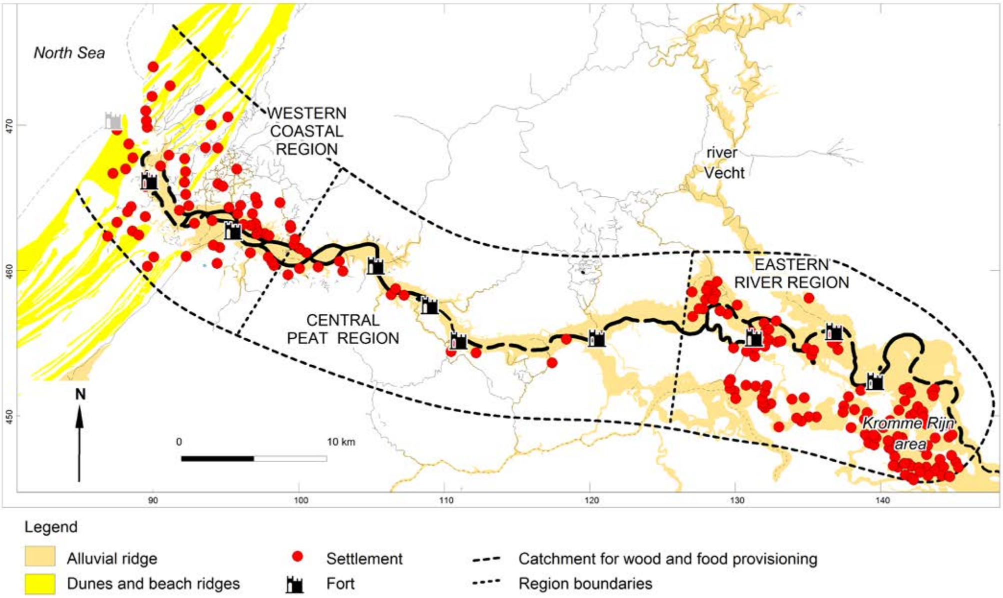

Figure 5.4 Reconstructed settlements in the western Lower Rhine Limes- zone based on ARCHIS database (2009; after Chapter 4).

the total military population in the research area is 4,550 persons in the Early Roman period and 7,700 in the Middle Roman period (Table 5.3).

5.3.2.2 Rural population

Based on the archaeological records in the national archaeological database ARCHIS, 210 settlements were reconstructed on the levees and the dunes in the research area (Chapter 4; Table C1 in Appendix C). Fig. 5.4 shows the location of reconstructed settlements. The distribution of the rural settlements over the research area is not uniform. The eastern and western regions seem to have been more densely populated than the central peat region. In these two regions, there were on average almost two settlements per km^2 high levee. According to Vos (2009, 214) such high settlement densities were only reached in the most densely inhabited regions of the Rhine-Meuse delta.

These settlements were not all inhabited contemporaneously; several were only inhabited during the Early or Middle Roman period. The number of settlements in the Rhine-Meuse delta increased during the first two centuries AD (Chapter 4). To account for the differentiation in settlement sizes, we use an average number of farmsteads per settlement, the so-called settlement-unit with 1.5 farmsteads, which were inhabited by c. 10 people for each rural settlement (Appendix C). The amount of land that was occupied by the settlement-units themselves is not taken into account in the model, because this turned out to be less than 5% on the levees and dunes in the Early and Middle Roman period (Appendix C).

These estimates and associated assumptions (Table C2 in Appendix C) lead to a reconstruction of 105 settlement-units in the Early Roman period and 177 in the Middle Roman period (Table C2

Table 5.4 The minimum number of reconstructed rural settlement-units per region and location north and south of the river Rhine.

	West	Central	East	Total
Early Roman period (AD 40 – 69)				
Northern dunes	10	-	-	10
Northern levees	9	9	10	28
Southern dunes	4	-	-	4
Southern levees	5	11	63	79
Total	*28*	*20*	*73*	***121***
Middle Roman period (AD 70 – 140)				
Northern dunes	10	-	-	10
Northern levees	9	9	10	28
Southern dunes	8	-	-	8
Southern levees	10	21	127	158
Total	*37*	*30*	*137*	***204***

in Appendix C). When considering that there were settlements that disappeared (e.g. by natural river erosion or excavation of sand or clay by human for raw material during later centuries) or so far have remained undiscovered, a correction was applied that leads to a minimum reconstructed number of settlements of about 120 in the Early Roman period and about 200 in the Middle Roman period (Table 5.4; Table C3 in Appendix C). In both periods 38 of these settlement-units were located north of the Rhine. This leads to a reconstruction of 1,200 people in the Early Roman period, a figure that nearly doubles to 2,000 in the Middle Roman period. This implies that the military population largely outnumbered the rural population in both time periods, roughly by a factor 3.5 (Tables 5.3 and 5.4).

5.3.3 Military demand

5.3.3.1 Wood demand

Wood research has shown that most timber was acquired locally (Chapter 4). This wood was acquired in various forests which differed in composition and structure from modern woodlands. As the yields from modern woodlands differed largely from those in Roman times, they could not be used for calculations. Therefore the yields of the Roman woodlands had to be estimated.

The yields from the Roman woodlands were estimated based on age and (estimated) diameters of (real or reconstructed) Roman tree remains (Staring, 1983; Jansma, 1995; Fokma, 1998; M.J. Kooistra *et al.,* 2006; Sass-Klaassen and Hanraets, 2006). Table 5.5 shows a comparison of these values with those of various taxa of modern trees. The differences are remarkable: remains of Roman tree trunks with diameters similar to modern trees usually contain many more year rings than modern trees. In other words, trees from Roman natural woodlands grew slower than present trees and were thinner than modern trees of the same age. Hence, the yields of Roman woodlands were lower than those of modern woodlands (Table 5.5). Based on these estimates, the wood yields were calculated for the various forest types present on the different geomorphological units in Roman times (Table 5.6). The resulting yields vary strongly among different woodland types. The lowest yields were obtained for the woodlands on the fens, while the highest yields would have come from alder coppices located on the lowest parts of the levees and the high parts of the flood basin.

Table 5.5 Estimates of the yields of Roman trees (in grey), on the basis of the differences between present-day and Roman woodlands, in ages and trunk diameters of the various taxa. Except for the reference of Casparie all references relate to modern data. The Roman data are distilled from archaeological and dendrochronological research carried out in the research area; * = an indication for the variations of wood accretion (in the production levels of wood volume), depending on factors such as soil types, hydrological regime, etc., ** = for fuel, *** = for timber (this number of rings is based on c. 40 counts of archaeological samples of alder) Reference: a. Jansen et al., 1996, b. yields of the 'bog fringing forest' are deduced from Casparie, 1982, 155, c. Clerckx et al., 1994, d. Ter Keurs pers. comm.

		Age		**Trunk diameter**		**Yields**	
Tree taxon	**Growth category***	**(from year of germination)**		**(at breast height in cm)**		**(in m^3/ha)**	
		Modern	Roman	Modern	Roman	Modern	Roman
						'Natural'	
Oak	3-4	80-120	82-122	15.8-23.3	10-20	105-171 [a]	100-125
Oak	5	80-120	123-244	38.2	34-40	247 [a]	
Oak	-	-	-	-	-	-	50-75 [b]
Alder/Oak/Birch	4	90	-	26.5	30-40	139 [a]	100
Alder	8	10-25	-	4.6-13.8	6-15	13-136 [a]	13-100
Ash/elm	4	90	58-217	22.5	25.5	195 [a]	175
Ash/elm	4	Up to 55		16.2	9-16.5	135 [a]	100
						Alder coppice	
Alder	-	30-40	-	-		80-230 [c]	200
Alder/Ash	-	8**	12***	8-10	7-15	200-250**** [d]	

According to the assumptions indicated in Appendix C, the total minimum estimated wood demand of the military population was 7.3 x 10^5 m^3 in the Early Roman period and rose to 28.7 x 10^5 m^3 in the Middle Roman period (Table 5.7; Table CTable C5 in Appendix C). The woodlands that most likely provided these quantities are shown in Table 5.7. These forests cover 61.9 km^2 in total in the Early Roman period and 202.3 km^2 in the Middle Roman period. Both the actual and the relative amounts of exploited woodlands differ per region and time period, depending on the population size and presence of different woodlands. It is assumed that in the Early Roman period only the high levees in the central peat region still carried substantial areas of natural mixed woodlands. The natural woodlands on the levees in the eastern river region and western coastal region were most probably already largely deforested, as these areas were relatively densely populated in pre-Roman times (Kooista *et al.,* 2013). Therefore, it is assumed that the Roman army stationed in the eastern region mainly exploited the flood basins and the fens downstream along the river Vecht. The forts in the western coastal region most likely retrieved part of their timber from the natural mixed woodlands on the levees in the peat area, only a few kilometres upstream. This is also suggested to Van Giffen in a letter from January 9th, 1943 by the palynologist F. Florschűtz, University of Utrecht, who performed the first pollen analysis for fort Valkenburg. By AD 70, these woodlands had been felled almost completely (Van Rijn, 2004). To cope with the disappearance of these resources, the Roman army probably found a permanent solution through the development of alder copses on the edge of the levees and in the flood basins. These copses could provide both timber and firewood.

Table 5.6 Estimated yields of Roman woodlands (with the main taxa found in the archaeological record and wood remains) on the different geomorphological units in the Lower Rhine Delta.

Geomorphological unit	Estimated wood yield (in m^3/ha)	Main taxa
Levee, high	100	Oak, maple, ash, elm
Levee, low	125	Alder, ash
Flood basin, high	125	Alder, willow
Coppice on low levees or high flood basin	200	Alder
Fen woodland	75	Oak, ash, alder
Barrier plains	100	Alder, willow

Table 5.7 Estimate of wood demand (m^3) for military population per region in the period between AD 40 and 140, converted into km^2 and divided over the woodlands on the most likely used different geomorphological units. Differences in total values are due to rounding; * partially retrieved in central peat area, ** (partially) retrieved north of the river Rhine.

	West		Central		East		Total	
	Timber	Fuel	Timber	Fuel	Timber	Fuel	Timber	Fuel
Early Roman period (AD 40-69)								
Demand (in m3 x 10^5)	0.3	1.4	0.4	1.8	0.6	2.8	1.4	6.0
	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2
Levee, high	1.1		1.9	1.8	3.1		6.2	1.8
Levee, low	0.9		0.8	7.3	1.3	11.0	2.9	18.4
Flood basin, high	0.8	5.5	0.8	3.7	1.3	11.0	2.8	20.2
Fen wood land	0.2			2.5			0.2	2.5
Barrier plains		6.9						6.9
Total	**3.0**	**12.4**	**3.4**	**15.3**	**5.7**	**22.1**	**12.1**	**49.8**
Middle Roman period (AD 70-140)								
Demand (in m3 x 10^5)	1.6	6.4	1.6	8.6	1.9	8.6	5.1	23.6
	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2
Levee, high								
Levee, low				20.6	4.5		4.5	20.6
Flood basin, high				20.6	4.5		4.5	20.6
Coppice on low levees or high flood basin	1.2	12.9	2.4	17.2	3.8	43.0	7.4	73.0
Fen wood land	17.9		15.2				33.0	
Barrier plains		38.6						38.6
Total	**19.1**	**51.5**	**17.6**	**58.4**	**12.8**	**42.9**	**49.5**	**152.8**

5.3.3.2 Demand of vegetable food

Cereals were the most important food for the Roman soldiers (Kooistra, 2009; idem, 2012; Chapter 4). Therefore, the calculations for the demand and supply of vegetable food are only based on the consumption of cereals. Although part of the cereals for the Roman army was imported from elsewhere, it is likely that a substantial part was obtained from local farmers and thus produced within the study area (Chapter 4). In our calculations we therefore assumed that 50% of the total military demand for cereals was derived from cereals that could be produced in the local surroundings. Based on the assumptions for the vegetable food demand (Appendix C), the estimated total energy requirement of locally produced cereals per year for the army and its

Table 5.8 Cereal demand for locally produced cereals, e.g. emmer and barley, (kCal) necessary to feed the Roman army and the *vicus* inhabitants per region in the period between AD 40 and 140, converted into areas of cultivated arable land with cereals and fallow land (km²).

	West	Central	East	Total
Early Roman period (AD 40-69)				
Energy needed for soldiers (kCal)	3.9×10^8	5.1×10^8	5.1×10^8	14.1×10^8
Energy needed for vici inhabitants (kCal)	0	0	2×10^8	2×10^8
Total energy needed for soldiers and vici (kCal)	3.9×10^8	5.1×10^8	7.1×10^8	16.1×10^8
Arable land needed for soldiers (km^2)	1.6	2.1	2.1	5.8
Fallow land needed for soldiers (km^2)	1.6	2.1	2.1	5.8
Arable land needed for vici inhabitants (km^2)	0	0	0.8	0.8
Fallow land needed for vici inhabitants (km^2)	0	0	0.8	0.8
Total arable + fallow land needed (km^2)	**3.2**	**4.2**	**5.8**	**13.2**
Middle Roman period (AD 70-140)				
Energy needed for soldiers (kCal)	3.9×10^8	5.1×10^8	5.1×10^8	14.1×10^8
Energy needed for vici inhabitants (kCal)	3.0×10^8	3.9×10^8	3.9×10^8	10.8×10^8
Total energy needed for soldiers and vici (kCal)	6.9×10^8	9.0×10^8	9.0×10^8	24.9×10^8
Arable land needed for soldiers (km^2)	1.6	2.1	2.1	5.8
Fallow land needed for soldiers (km^2)	1.6	2.1	2.1	5.8
Arable land needed for vici inhabitants (km^2)	1.2	1.6	1.6	4.4
Fallow land needed for vici inhabitants (km^2)	1.2	1.6	1.6	4.4
Total arable + fallow land needed (km^2)	**5.6**	**7.4**	**7.4**	**20.4**

associates in the research area was 16.1×10^8 kCal in the Early Roman period and 24.9×10^8 kCal in the Middle Roman period (Table 5.8). The total area of cultivated arable fields needed to feed the army and its entourage with emmer and barley was 6.6 km². In the Middle Roman period, when *vici* appeared around all forts, 10.2 km² of arable fields would have been required for cereal production. As the model is based on a two-course rotation, this means that the abovementioned areas need to be multiplied by two, resulting in a total of about 13 km² in the Early Roman period and about, 20 km² in the Middle Roman period (Table 5.8).

5.3.3.3 Demand of animal food

Because cattle was the main meat provider of the army, the calculations for the demand and supply of domestic meat and meat products are only based on the consumption of beef (Chapter 4). As no data are available on the size and calorific value of cattle herds kept by the farmers in the Roman period in the Rhine-Meuse delta and the amount of land needed for pasture, these parameters are estimated by combining data on herd size, composition, slaughter patterns, and calorific values from several studies (Gregg, 1988; Lauwerier, 1988; IJzereef, 1981; Meffert, 1998). According to Gregg (1988), the minimum size of a viable herd is at least 30 heads in winter time. Based on our assumptions, such a herd will annually yield a total of 2.3×10^6 kCal (Table C6 in Appendix C). As a settlement-unit needs 1.8×10^6 kCal of meat products yearly (Appendix C, ad 3.4.3), this would leave 0.5×10^6 kCal – equivalent to almost one cow a year – to the settlement as surplus for exchange or storage, feasting, ritual etc. As this herd size does not yield a significant surplus of

Table 5.9 Calculations of pasture needed for a herd composition of 50 heads in winter. Food intake is calculated to the equivalent of mature cows (1 mature cow taken as 100%; see also Gregg, 1988, 107).

Herd composition	Number in winter when fed hay	Food intake (% of mature cow)	Total intake herd for hay (as number of mature cow)	Number in grazing period	Food intake (% of mature cow)	Total intake herd for pasture (as number of mature cow)
Calf	0	0	0	15	15	2.25
Up to 1 year	12	80	9.6	0	0	0
Heifer	10	80	8	22	80	17.6
Oxen	7	100	7	7	100	7
Cow	19	100	19	19	100	19
Bull	2	100	2	2	100	2
Total	**50**	-	**45.60**	**65**	-	**47.85**

meat for the Roman army, a herd size of 50 heads in winter time was taken as the basis for further calculations. A herd of this size has a different composition and size structure than one with 30 heads. The increase results in a proportionally different slaughter pattern. A herd of 50 heads will annually yield 3.8 x 10^6 kCal (Table C.7 in Appendix C). This means that a herd of 50 heads may produce a yearly surplus of c. 2.0 x 10^6 kCal, an equivalent of c. 4 mature cows.

We assume that the herds grazed on the pastures and fallow land. After harvesting, they could also feed on the stubble left on the arable fields. During the winter period, lasting four months, they were fed with hay. Yet, the herd size is not stable throughout the year. Calving, natural deaths and slaughter influence the herd size. Therefore, different numbers were used to calculate the hay and grass consumption. Table 5.9 shows the size and relative food intake of each age group during the year. During the winter months an equivalent of 45.6 mature cows were used for calculations on hay consumption and during the grazing season an equivalent of 47.9 cows for pasture.

Based on three bovines per ha, the areas needed for pasture of a herd of 50 heads amounts to 16 ha (section 3.4.3 in Appendix C). In addition, hay meadows were needed to produce fodder for the winter period. As a herd of 50 heads would consume hay to the equivalent of 45.6 mature cows and assuming a high annual yield of 3400 kg hay per ha, at least an extra 10.1 ha of meadow was needed to sustain the herd's needs during the winter months (section 3.4.2 in Appendix C). Hence, an area of at least 26.1 ha of pasture and meadow was needed to sustain a viable herd of 50 heads. Assuming a fallow system was used for crop cultivation (section 5.3.3.2), the additionally required land for pasture and meadows by a settlement-unit to sustain a herd was reduced by the amount of fallow land, which is 3.3 ha per settlement-unit (section 3.4.2 in Appendix C).

Based on the assumptions for the demand of meat (Appendix C), the total energy requirement of meat per year for the army and its associates in the research area is reconstructed at 10.7 x 10^8 kCal in the Early Roman period and 16.5 x 10^8 kCal in the Middle Roman period (Table 5.10). As one herd of 50 heads produced a yearly surplus of 2.0 x 10^6 kCal, the reconstructed settlement-units would have been able to produce 2.4 x 10^8 kCal in the Early Roman period and 3.3 x 10^8 kCal in the Middle Roman period (Table 5.10). This, however, is only 20-25 % of the meat required for the army; none of the regions would have been able to produce enough animal food for the army in both periods. This apparent deficit means that the number of herds needed was larger. An extra herd of 50 heads would yield a surplus of 3.8 x 10^6 kCal, as the demands of the rural settlement-units in the area were already fulfilled. Thus, 219 extra herds of 50 heads would be needed in the Early Roman period, roughly corresponding to two additional herds per settlement-unit when distributed evenly

Table 5.10 Demand of meat (kCal) necessary to feed the Roman army and the *vicus* inhabitants per region in the period between AD 40 and 140, converted into numbers of herds and areas of pasturage and meadow needed for extra herds (based on surplus production of herds of 50 heads in wintertime).

	West	Central	East	Total
Early Roman period (AD 40-69)				
Energy needed for soldiers (kCal)	2.6×10^8	3.4×10^8	3.4×10^8	9.4×10^8
Energy needed for vici inhabitants (kCal)	-	-	1.3×10^8	1.3×10^8
Total energy needed for soldiers and vici (kCal)	2.6×10^8	3.4×10^8	4.7×10^8	10.7×10^8
Rural settlements (keeping one herd of 50 heads) (N)	28	20	73	121
Surplus production of rural settlements (kCal)	0.6×10^8	0.4×10^8	1.4×10^8	2.4×10^8
Extra herds needed to feed Roman army and vici (N; excl. domestic need)	53	80	86	219
Pasture needed for extra herds (km²)	*8.5*	*12.8*	*13.8*	*35.0*
Meadows needed for extra herds (km²)	*5.4*	*8.1*	*8.7*	*22.1*
Total of herds needed to feed Roman army, vici and domestic need of settlement-units (N)	**81**	**100**	**159**	**340**
Middle Roman period (AD 70-140)				
Energy needed for soldiers (kCal)	2.6×10^8	3.4×10^8	3.4×10^8	9.4×10^8
Energy needed for vici inhabitants (kCal)	1.9×10^8	2.6×10^8	2.6×10^8	7.1×10^8
Total energy needed for soldiers and vici (kCal)	4.5×10^8	6.0×10^8	6.0×10^8	16.5×10^8
Rural settlements (keeping one herd of 50 heads) (N)	18	21	127	166
Surplus production of rural settlements (kCal)	0.4×10^8	0.4×10^8	2.5×10^8	3.3×10^8
Extra herds needed to feed Roman army and vici (N; excl. domestic need)	109	147	92	348
Pasture needed for extra herds (km²)	*17.4*	*23.5*	*14.7*	*55.7*
Meadows needed for extra herds (km²)	*11.0*	*14.8*	*9.3*	*35.1*
Total of herds needed to feed Roman army, vici and domestic need of settlement-units (N)	**127**	**168**	**219**	**514**

(Table 5.10). These extra herds would by themselves require an extra land use for the Roman army and the *vici* inhabitants of 57.1 km², distributed over 35 km² of pasture and 22.1 km² of meadows (Table 5.10). Together with the land in use by the settlement-units (Tables 5.13 and 5.15a), the total area needed for animal husbandry in the Early Roman period would be 84.7 km², of which 50.4 km² needed for pasturage and 34.3 km² as meadow.

For the Middle Roman period, with a reconstructed number of 166 settlements south of the river Rhine and an increased number of *vici* inhabitants, the need for extra herds increased to 348, adding up to a total of 514 herds of 50 heads (Table 5.10). So again, when distributed evenly, each settlement-unit had to take care of approximately three or even four herds. These extra herds would require an extra 90.8 km². This figure would, together with the land used by the local population (Tables 5.13 and 5.15b) add up to a total of 128.7 km², distributed over 76.8 km² of pasture and 51.9 km² of meadow. This would be the absolute minimum of land needed for animal husbandry to sustain the Roman army and its associates in the research area in this period with meat (Table 5.10).

5.3.4 Rural demand and supply

5.3.4.1 Wood demand

There is little information on the wood used for farms and barns in the rural settlements in the research area in the 1st and 2nd cenuries AD (Lange, 2009). Rural settlements in other areas provide

Table 5.11 Minimum wood consumption for timber and fuel (m^3) for agrarian settlements per region in the period between AD 40 and 140, converted into km^2 and divided over the woodlands on the most likely used different geomorphological units. Differences in total values are due to rounding.

	West		Central		East		Total	
	N	S	N	S	N	S	N	S
Early Roman period (AD 40-69)								
demand (in m^3 x 10*5)	0.1	0.7	0.1	0.1	0.1	0.1	0.3	0.9
	km^2		km^2		km^2		km^2	
Levee, high	0.11	-	-	-	-	-	0.11	-
Levee, low	0.09	-	-	-	0.46	2,89	0.55	2.89
Flood basin, high	0.09	0.10	0.04	-	0.46	2,89	0.59	2.98
Fen wood land	-		1.31	1.68	-	-	1.31	1.68
Barrier plains	0.78	0.48	-	-	-	-	0.78	0.48
Total	**1.06**	**0.58**	**1.35**	**1.68**	**0.92**	**5,77**	**3.33**	**8.03**
Middle Roman period (AD 70-140)								
demand (in m^3 x 10*5)	0.3	0.3	0.2	0.6	0.3	3.5	0.8	4.3
	km^2		km^2		km^2		km^2	
Levee, low		0.12		1.44		-		1.56
Flood basin, high		0.12		1.44		-		1.44
Barrier plains		1.30		-		-		-
Coppice on low levees or high flood basin		0.65		1.2		17.5		18.70
Total		**2.19**		**4.08**		**17.5**		**21.70**

information that mostly alder, ash and oak had been used for construction (Van Rijn, 1995; idem, 2003; Vorst and Hanninen, 2005) and that is most likely the case here too. The quantity of timber and firewood is estimated per settlement-unit (Table C8 in Appendix C). Based on these assumptions the total wood demand of the rural settlements is calculated at c. 1.2 x10^5 m^3 in the Early Roman period and rises to 5.1 x10^5 m^3 in the Middle Roman period (Tables 5.11 and C.8 in Appendix C). The forests that most likely provided these quantities cover 11.4 km^2 in total in the Early Roman period and 21.7 km^2 south of the river in the Middle Roman period. The quantities needed are very small and almost negligible compared to those used by the army and the *vici* in both periods (Table 5.7). The rural settlements in both periods were in all probability supplied by alder retrieved from woodlands nearby. In the Early Roman period, the wood is assumed to be derived from the various natural woodlands on the levees and in the flood basin, the fen woodlands and the barrier plains. In the Middle Roman period, natural woodlands on the levees and flood basin had become scarce. There are strong indications that a system of wood management was introduced and that most wood was acquired from alder coppices established on the high flood basins. With the development of these alder coppice it is likely that the rural population became involved in the management. The appearance of farm buildings of native character in the 2nd century, for example on the site of Valkenburg-Marktveld (Hallewas *et al.,* 1993, 37-42) in former military territory could be interpreted in this view.

5.3.4.2 Arable farming

The rural population was autarchic in food supply; cereals were the primary vegetable food component (Chapter 4). Based on the assumptions of vegetable food demand, one settlement-unit

Table 5.12 Areas of arable and fallow land (in km²) needed to feed the rural population per region and period; N = north of the river Rhine; S = south of the river Rhine.

	West		Central		East		Total	
	N	S	N	S	N	S	N	S
Early Roman period (AD 40-69)								
Settlements (N)	19	9	9	11	10	63	38	83
Arable land for own use (km^2)	0.6	0.3	0.3	0.4	0.3	2.1	1.3	2.7
Fallow land for own use (km^2)	0.6	0.3	0.3	0.4	0.3	2.1	1.3	2.7
Total land needed for own use (km^2)	**1.2**	**0.6**	**0.6**	**0.8**	**0.6**	**4.2**	**2.6**	**5.4**
Middle Roman period (AD 70-140)								
Settlements (N)	19	18	9	21	10	127	38	166
Arable land for own use (km^2)	0.6	0.6	0.3	0.7	0.3	4.2	1.3	5.5
Fallow land for own use (km^2)	0.6	0.6	0.3	0.7	0.3	4.2	1.3	5.5
Total land needed for own use (km^2)	**1.2**	**1.2**	**0.6**	**1.4**	**0.6**	**8.4**	**2.6**	**11**

needed 3.3 ha to satisfy its own needs for cereal food (Appendix C). The minimum amount of land necessary to feed the total rural population in the Early Roman period amounts to 8.0 km², distributed over 2.6 km² north of the river and 5.4 km² south of the river Rhine (Table 5.12). In the Middle Roman period, the number of settlements south of the river doubled and therefore 13.6 km² was needed of which 11 km² was located south of the river Rhine. These areas were smaller than those required to fulfil the demand of the military population, but less than the ratio of the population sizes because we assumed that the military population imported part of the consumed cereals, e.g. spelt wheat and bread wheat (Appendix C; 50%).

5.3.4.3 Animal husbandry

Cattle was the main meat provider in agrarian settlements during the entire Roman period (Chapter 4). In our model, meat products consumed by the rural population were entirely obtained from their own cattle. A settlement-unit needed c. 1.8 x 10^6 kCal per year (Appendix C). With one herd of 50 heads per settlement-unit and each herd requiring at least 16 ha of pasture and 10.1 ha of hay

Table 5.13 Areas of pasturage and hay land needed (in km²) for animal husbandry to feed rural population per region and period (based on one herd of 50 heads in wintertime per settlement-unit). Difference in total values are due to rounding; N = north of the river Rhine; S = south of the river Rhine.

	West		Central		East		Total	
	N	S	N	S	N	S	N	S
Early Roman period (AD 40-69)								
Settlements = herds (N)	19	9	9	11	10	63	38	83
Land needed for husbandry (km^2)	**4.3**	**2.1**	**2.1**	**2.5**	**2.3**	**14.4**	**8.7**	**18.9**
Pasture (km^2)	***2.4***	***1.1***	***1.1***	***1.4***	***1.3***	***8.0***	***4.8***	***10.5***
Meadow (km^2)	***1.9***	***0.9***	***0.9***	***1.1***	***1.0***	***6.4***	***3.8***	***8.4***
Middle Roman period (AD 70-140)								
Settlements = herds (N)	19	18	9	21	10	127	38	166
Land needed for husbandry (km^2)	**4.3**	**4.1**	**2.1**	**4.8**	**2.3**	**29.0**	**8.7**	**37.8**
Pasture (km^2)	***2.4***	***2.3***	***1.1***	***2.7***	***1.3***	***16.1***	***4.8***	***21.1***
Meadow (km^2)	***1.9***	***1.8***	***0.9***	***2.1***	***1.0***	***12.8***	***3.8***	***16.8***

meadow (Appendix C). As seen above (section 5.3.4.2) a fallow system was used for crop cultivation; the additionally required land for pasture by a settlement-unit to sustain a herd was reduced by the amount of fallow land, which is 3.3 ha per settlement-unit (section 3.4.2 in Appendix C). The minimum area necessary to feed the total rural population in the Early Roman period amounts to 8.7 km² north of the river and 18.9 km² south of the river Rhine (Table 5.13). In the Middle Roman period, when the number of settlements south of the river had doubled, accordingly requiring 37.8 km² of pasture and meadow land south of the river Rhine.

5.3.4.4 Rural surplus production

Arable farming

We assumed that the agrarian population had to produce cereals for the army, in addition to the production of their own consumption, and that the soldiers and the *vicani* did not contribute to the production process. As manpower is essential for the cultivation of cereals, this implies that the rural labour potentially forms a constraint for the surplus production for the Roman army. In the process of grain production, the labour exertion during harvest is a potential bottleneck. Ploughing, sowing, and working the soil can be accomplished by a small number of people over a longer period of time. Harvest time, on the other hand, is limited, because if the grain remains in the field too long after ripening, the ears fall apart before they can be harvested. In addition, the chance that the ripe grain will be eaten by, for example, birds or mice, increases the longer it remains in the field. Therefore, the harvest had to be completed within two weeks (Gregg, 1988).

The potential cereal surplus production capacity per region per time period based on the availability of extra labour provided by the rural settlements is shown in Table 5.14. In the Early Roman period, the maximum amount of available labour for surplus production allows cultivation of 7.4 km² north of the river and 15.8 km² south of the river, or 23.2 km² in total. In the Middle Roman period, when we assume that only the settlements south of the river delivered surplus production, the available labour capacity allowed cultivation of 31.6 km² of land. When this surplus production capacity is compared to the demand of the Roman army and its associates, it turns out that in both the Early and Middle Roman period the total number of reconstructed settlement-units was large enough to provide extra labour for surplus production. However, the amounts of the surplus production differed per region. In the Early Roman Period, the rural settlements south of the river Rhine in the eastern river region alone could have provided sufficient surplus for that region, while the forts in the central peat region and in the western coastal region could only have been supplied with enough emmer and barley if the settlements on the northern side of the Rhine helped in providing it. In the Middle Roman period, when we assume that only settlements south of the river produced surplus for the Roman army, shortages must have occurred in the central peat region and in the western coastal region. However, the agrarian population of the eastern river region would have been able to produce enough emmer and barley not only for the military and *vici* inhabitants stationed in the region, but also to supplement the production deficiencies in the central peat and western coastal regions.

Cereal transport

The imported cereals for the Roman army, e.g. spelt wheat and bread wheat, were most likely transported by ship, either over the North Sea and up the river, or by navigating downstream on the rivers Rhine or Meuse (Haalebos, 1997a). Cereals that were produced by the local rural population were probably also preferably transported by ship, along the rivers and many smaller tributaries

Table 5.14 Number of settlements and estimated areas of arable land (in km²) available for surplus production based on labour capacity (A), the demand of the military population (B) and the net result (A-B) per time period and per region; N = north of the river Rhine; S = south of the river Rhine.

	West		Central		East		Total	
	N	**S**	**N**	**S**	**N**	**S**	**N**	**S**
Early Roman period (AD 40-69)								
Settlements (N)	19	9	9	11	10	63	38	83
Potential arable land available for surplus production (km^2)	1.8	0.9	0.9	1.0	1.0	6.0	3.7	7.9
A. Sum arable fields (km^2)	2.7		1.9		7.0		11.6	
B. Arable land needed for demand of military population (km^2)	1.6		2.1		2.9		6.6	
Net result (A-B), surplus (+) or deficit (-) of arable land (km^2)	*1.1*		*- 0.2*		*4.1*		*5.0*	
Extra settlements needed to compensate deficit (N)	-		*2*		-		-	
Middle Roman period (AD 70-140)								
Settlements south of the Rhine (N)	-	18	-	21	-	127	-	166
A. Potential arable land available for surplus production (km^2)	-	1.7	-	2.0	-	12.1	-	15.8
B. Arable land needed for demand of military population (km^2)	-	2.8	-	3.7	-	3.7	-	10.2
Net result (A-B), surplus (+) or deficit (-) of arable land (km^2)	-	*-1.1*	-	*-1.7*	-	*8.4*	-	*5.6*
Extra settlements needed to compensate deficit (N)	-	*9*	-	*14*	-	-	-	-

in the *Limes*- zone. Because not all cereal-producing farms were positioned along waterways, the cereals must have been transported over land over short distances. It is likely that cattle belonging to the local herds were used for this. Therefore, our model does not account for extra draught cattle in the rural population.

Animal husbandry
In order to calculate the surplus production of animal food, initially the surplus of the herds of the settlement-units is assumed to be used for the army's demand for meat. In section 5.3.3.3, we have seen that when taking one herd of 50 heads per settlement-unit, in both periods c. three-quarters of the yearly demand for meat from the army cannot be met (Table 5.10). Therefore, the number of extra herds required to meet this demand was calculated in that paragraph. Since the needs of the local population were already satisfied by the yield of their own herd, the total yield of these extra herds can be supplied to the Roman army as surplus. It has already been established earlier that in both the Early and Middle Roman periods each settlement-unit had to keep at least two to three extra herds on average to meet the total demand from the army. However, the settlements are not evenly spread over the landscape in the research area. This picture becomes even stronger in the Middle Roman period when only the settlements on south of the river Rhine are supposed to produce for the Roman army and its associates. When we look at the individual regions, it becomes clear that due to the limited number of reconstructed settlements in the central peat and western coastal region even more herds per settlement-unit would have been necessary there, while in the eastern river region only c. one herd extra was needed per settlement-unit (Table 5.10).

Draught cattle

To satisfy the demands of the Roman army, our model assumes that the local farmers bred more cattle. Some of these would have been used temporarily as draught animals. Therefore, it was not necessary to breed even more cattle to supply sufficient draught power for the ploughing of a larger number of fields. After being used as draught animals, the cattle could still be supplied to the army as food. Archaeozoological research on the fortr at Alchester where relatively older animals were present than in the contemporary sites from the region (Thomas, 2008), suggests that the army was indeed supplied with cattle that had first been used as draught animals.

5.4 Discussion

5.4.1 Land availability and suitability

Table 5.15 shows the total area of land that is available and the amount of land which is minimally necessary to provision the entire population, i.e. the rural settlements plus the Roman army and *vici*, with wood and locally produced plant and animal food. The comparison indicates that the landscape in the research area did not form a limiting factor for supplying the necessary amount of wood, cereals and animal products to the rural settlements as well as to the Roman army and its associates during the Early Roman period (Table 5.15a). Timber, cereals and fodder could largely be retrieved from different landscape units, thereby avoiding conflicting spatial demands (Chapter 4). However, during Middle Roman period the limits of the landscape started to pose an upper limit on land availability, mainly because wood demands rose to immense amounts because of population rise (Table 5.15b).

Timber could be collected from the various types of woodland that grew on the levees and in the flood basin as well as the vast fen woodlands further away. This is in agreement with the wood remains of Roman military constructions, which show that most of the timber used in military constructions came from local woodlands. In the Early Roman period, the natural old woodlands on the levees and the natural alder wetland woodlands on the higher parts of the flood basins were felled. Later on, timber wood was mainly obtained from the alder copses established on the low levees and flood basins, but also from woodlands on the peat situated more inland (Table 5.15b).

Cereals could only have been cultivated on the higher parts of the levees and the dunes. Table 5.15 shows that enough potentially suitable land was present for this purpose, assuming that only 50% of the cereals consumed by the soldiers and vici inhabitants consisted of locally produced cereals, even if only fields were utilized that were located on the levees and dunes south of the river Rhine. Thus, the landscape was not necessarily a limiting factor in the supply of locally produced cereals, e.g. emmer and barley, to the Roman army and the *vici*.

Livestock probably grazed on the low parts of the levees and in the fertile flood basin (Table 5.15). Furthermore, both the fallow land and the stubble fields provided supplementary food for the animals. Finally, animal fodder could be harvested on the low parts of the levee and in the high parts of the flood basin. And although we assume that only the settlements on the south bank provided supplies in the Middle Roman period, grazing may have taken place on both sides of the river Rhine in the flood basin, only needing a few extra guards against cattle thieves. The landscape was thus not a limiting factor for the grazing area of the herds needed to provide enough meat for the total population in the research area.

According to our estimates, roughly 25% of the levees, flood basins and dunes were required for wood and food provisioning during the Early Roman period, rising to c. 75% in the Middle Roman

Period. These figures are minimum estimates as our calculations are based on estimates of minimum population sizes, maximum surplus labour capacity per rural settlement and constant and optimal harvest yields. For the Early Roman period this minimum required area is only a quarter of the available landscape; and even if the real requirement would have been twice as large, this area was still available. Therefore, we are confident that in the Early Roman period the landscape did not limit local supply. However, if the results are indeed under-estimates of the real numbers, this implies that in the Middle Roman period the landscape may have limited a completely local supply. Possible shortage of land for the arable farming and animal husbandry could be overcome by retrieving a (larger) part of the wood from the northern side of the river Rhine and/or using the levees and flood basins to the north as arable, grass and/or hay land.

Table 5.15 Area of land available (in km²) versus the minimum amount of land (in km²) needed to provide the rural and military population with wood (brown), cereals (yellow) and meat (green) per region and time period and distributed over the potential suitable landscape units. In the Middle Roman period, the supply for the military population was no longer derived from land located north of the river Rhine (Kooistra, 2009; Appendix C: 3.3.2); * = bordering flood basin, **= partially retrieved in central peat area, *** = corrected for use of fallow land for grazing, **** (partially) retrieved north of river.

Early Roman period (AD 40-69)

<table>
<tr><th></th><th>Salt marsh</th><th>Sedge and reed marsh*</th><th>Dune</th><th>Levee, high</th><th>Levee, low</th><th>Flood basin, high</th><th>Flood basin, low</th><th>Fen wood-land</th><th>Barrier plain with fen woodland</th></tr>
<tr><td></td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td></tr>
<tr><td colspan="10">Western coastal region</td></tr>
<tr><td>Available land</td><td>2</td><td>30</td><td>36</td><td>17</td><td>16</td><td>22</td><td>43</td><td>27</td><td>17</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>1.2**</td><td>1.0</td><td>6.5</td><td>-</td><td>0.2</td><td>8.2</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>5.6</td><td></td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland***</td><td></td><td>-</td><td colspan="4">12.0</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td></td><td colspan="6">8.1</td><td>-</td><td>-</td></tr>
<tr><td colspan="10">Central peat region</td></tr>
<tr><td>Available land</td><td>-</td><td>6</td><td>-</td><td>39</td><td>18</td><td>18</td><td>50</td><td>140</td><td>-</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>3.8</td><td>8.1</td><td>4.5</td><td>-</td><td>5.4</td><td>-</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>-</td><td>5.6</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland***</td><td>-</td><td>-</td><td>-</td><td colspan="3">15.3</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td></td><td>-</td><td colspan="4">10.1</td><td>-</td><td>-</td></tr>
<tr><td colspan="10">Eastern river region</td></tr>
<tr><td>Available land</td><td>-</td><td>8</td><td>-</td><td>105</td><td>27</td><td>34</td><td>75</td><td>8</td><td>-</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>3.1</td><td>15.6</td><td>15.6</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>-</td><td>10.6</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland***</td><td>-</td><td>-</td><td>-</td><td colspan="3">23.0</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td></td><td>-</td><td colspan="4">16.1</td><td>-</td><td>-</td></tr>
<tr><td colspan="10">Total</td></tr>
<tr><td>Available land</td><td>2</td><td>44</td><td>36</td><td>161</td><td>61</td><td>74</td><td>168</td><td>175</td><td>17</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>8.1</td><td>24.8</td><td>26.6</td><td>-</td><td>5.7</td><td>8.2</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>21.8</td><td></td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland***</td><td></td><td>-</td><td colspan="4">50.4</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td></td><td colspan="6">34.3</td><td>-</td><td>-</td></tr>
</table>

5.4.2 Labour availability

The size of the rural population did form a limiting factor for the provisioning of the army and its associates with locally produced food. The largest problem arose for the meat supply. The rural settlements had to increase the amount of livestock and on average take care of c. three herds of 50 heads per settlement-unit both in the Early and Middle Roman period. This would amount to 150 animals in wintertime. We think this is implausible, especially as no archaeological data are available that point to keeping larger herds, such as an increased number of stable boxes in the byre-houses, or the construction of extra sheds where animals could be housed. We think that even when the herds were kept outside all year long, which is most likely as the winters are fairly mild in the Netherlands and the cattle was much sturdier than nowadays, some stable capacity would have been necessary, especially for cattle used for extra labour and providing milk. But more importantly, the amount of extra (herding) labour was probably strongly limited in the Early Roman period because of incomplete households as local farmers were recruited as Roman soldiers (Tacitus, *Germania* 29; *Historiae* 4.12, 17). It is assumed that this recruitment was replaced by taxing in the Middle Roman period (Groot *et al.,* 2009). Although it is often supposed that herding was a children's task, it seems impossible for the children of one settlement-unit to herd c. 150 animals and even more in summer. Another aspect to take into account is the distribution of the settlements throughout the landscape:

Middle Roman period (AD 70-140)

<table>
<tr><th></th><th>Salt marsh</th><th>Sedge and reed marsh*</th><th>Dune</th><th>Levee, high</th><th>Levee, low</th><th>Flood basin, high</th><th>Flood basin, low</th><th>Fen wood-land</th><th>Barrier plain with fen woodland</th></tr>
<tr><td></td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td><td>(km²)</td></tr>
<tr><td colspan="10">Western coastal region</td></tr>
<tr><td>Available land</td><td>1</td><td>7</td><td>18</td><td>11</td><td>9</td><td>12</td><td>17</td><td>17</td><td>5</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>-</td><td colspan="2">14.2</td><td>-</td><td>17.9</td><td>38.8</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>6.8</td><td></td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland***</td><td></td><td>-</td><td colspan="4">19.7</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td></td><td colspan="6">12.8</td><td>-</td><td>-</td></tr>
<tr><td colspan="10">Central peat region</td></tr>
<tr><td>Available land</td><td>-</td><td>6</td><td>-</td><td>22</td><td>10</td><td>10</td><td>27</td><td>77</td><td>-</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>-</td><td colspan="2">59.7</td><td>-</td><td>15.2 ****</td><td>-</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>-</td><td>8.8</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland***</td><td>-</td><td>-</td><td>-</td><td colspan="3">26.2</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td></td><td>-</td><td colspan="4">17.0</td><td>-</td><td>-</td></tr>
<tr><td colspan="10">Eastern river region</td></tr>
<tr><td>Available land</td><td>-</td><td>-</td><td>-</td><td>73</td><td>19</td><td>24</td><td>45</td><td>-</td><td>-</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>-</td><td colspan="2">57.8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>-</td><td>15.8</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland***</td><td>-</td><td>-</td><td>-</td><td colspan="3">30.8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td>-</td><td>-</td><td>-</td><td colspan="4">22.1</td><td>-</td><td>-</td></tr>
<tr><td colspan="10">Total</td></tr>
<tr><td>Available land</td><td>1</td><td>13</td><td>18</td><td>106</td><td>38</td><td>46</td><td>89</td><td>94</td><td>5</td></tr>
<tr><td>Woodland</td><td>-</td><td>-</td><td>-</td><td>-</td><td colspan="2">131.7</td><td>-</td><td>54.7 ****</td><td>38.8</td></tr>
<tr><td>Arable land</td><td>-</td><td>-</td><td>31.4</td><td></td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Grassland***</td><td></td><td>-</td><td colspan="4">76.8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Hay land</td><td></td><td colspan="6">51.9</td><td>-</td><td>-</td></tr>
</table>

in densely populated areas, the herdsmen would have to take their animals to fields at considerable distances from their homes. So, it is likely that the majority of the meat products was imported, probably extra-regionally, for instance from the densely occupied central Dutch river area (Vossen, 2003; Heeren, 2009, 191) or additional supply came from other sources such as pork, sheep and goat, or fishing and fowling (see also section 5.4.3). The way transport of (live or dead) animals or meat products was organised and the problems it posed will not be discussed in this chapter.

The reconstructed number of settlements in the peat region during the Early Roman period, and in the peat and coastal region during the Middle Roman period was too low to provide enough labour power during harvest time of the locally grown cereals, e.g. emmer wheat and barley. However, the rural labour capacity and the carrying capacity of the landscape for surplus production of cereals in the river area were sufficiently large to overcome this problem. Again, incompleteness of households may also have limited the labour availability for cereal production. Thus, the actual surplus production might have been smaller in the Early Roman period than calculated. The total storage capacity in the settlements, indicated by the number and size of the granaries, increased from the 40s AD onwards and in the 2nd century the storage capacity exceeded the demand for the local community (Groot *et al.,* 2009; Heeren, 2009). This suggests that rural settlements in the Middle Roman period were indeed capable of substantial surplus production, and that the associated extra labour capacity was available.

We assume that the tree felling and management of the woodlands were governed by the Roman army or its associates, and that the soldiers themselves were involved in wood cutting. It is unknown whether the rural population was also (structurally) employed for this task. If so, the rural labour capacity for felling trees was probably enough to fulfil the daily needs of wood, but prior to intensive building campaigns of the Roman army their capacity was probably too low. Furthermore, employment of local farmers would not have been possible during periods of harvest and slaughter.

Periods and intensity of the different provisioning activities varied throughout the year (Fig. 5.5). During certain time periods several activities coincided, for example during late autumn with the slaughtering of cattle, ploughing of the fields and wood felling. To avoid this leading to labour shortage, activities might have been shifted in time. For example, wood cutting might have been postponed from autumn to the winter period. To overcome temporary labour shortages during periods of peak activitieernal labour force may also have been attracted, consisting either of military personnel, seasonal workers from elsewhere or a combination of both. It is likely that the soldiers were at least employed during the building of the military structures like forts, watchtowers and roads. During summertime the soldiers had their military duties and therefore it is assumed that they were not involved in cereal harvesting. If besides the rural population extra assistance was indeed called upon, the logistics were probably so complex that only a tight organisation, like the Roman army, could have directed such authority. If these workmen were already inhabitants of the *vici*, their provisioning is included in the calculations; if not, extra supplies were needed temporarily.

5.4.3 Parameter uncertainties

The model consists of many parameter values that influence the model outcome. The assigned parameter values are based on a large number of assumptions, inevitably leading to considerable uncertainties. While it was impossible to estimate all uncertainties and to undertake a full uncertainty assessment we will address here the main sources of uncertainty and the potential implications for the obtained results.

The landscape reconstruction, which forms the template for the provisioning of wood and food, is based on high-resolution data (Chapter 2). Errors in the size of different landscape units

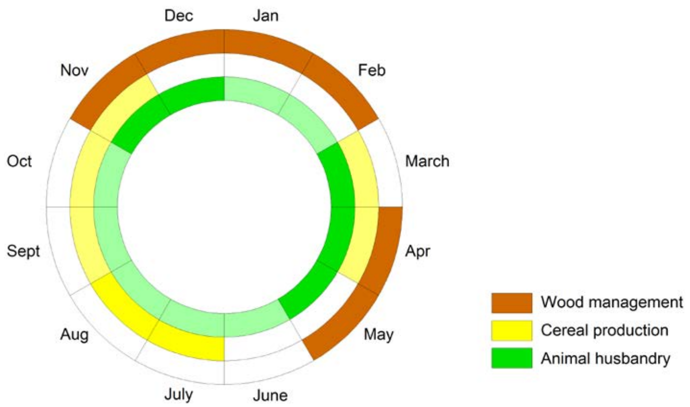

Figure 5.5 Employment of workmen needed for harvesting of wood, production of cereals and animal food production during the year (intensity of colour reflects labour intensity).

within the research area are less than a few km² per unit, implying no significant change in the interpretation of land availability in Roman times.

Our main concern is the reconstruction of the rural population size. The calculations are based on a minimum number of reconstructed settlement-units (Table 5.4). However, it is possible that the number of undiscovered settlements is underestimated, especially in the central peat region and in the dune area. Therefore, we performed a *maximum* calculation in which we assumed a uniform, maximum density on the high levees and dunes of one settlement-units/km² both north and south of the river in the Early Roman period, and one settlement-unit/km² north of the river Rhine and two settlement-unit/km² south of the river in the Middle Roman period (Table 5.16). These estimates led to a reconstruction of c. 200 settlement-units in the Early Roman period and over 300 in the Middle Roman period. This is almost a doubling of the total numbers when compared to our minimum estimate of settlement-units.

If the rural population did indeed reach these maxima, wood consumption would have increased, but the demand of the local population was relatively smaller when compared to the demand of the military population. The vast fen woodlands north and south of the Rhine formed an almost inexhaustible source of wood. Neither would the area of land needed to supply the total population in the area with food have posed a problem. Moreover, the rural population would have had a larger surplus of labour capacity and therefore have been able to produce more cereal surplus. This would imply that every region would have been able to produce enough to provision the army stationed in that region (Table 5.16 vs Table 5.14). However, each settlement still would have had to guard implausibly large herds, i.e. 100 heads. It is unlikely that this maximum settlement density was reached in the whole research area, especially not in the peat region. The true population size probably lies somewhere in between these minimum and maximum reconstructions.

Another significant uncertainty in the model is the number of soldiers stationed in the research area and the associated number of *vicus* inhabitants. If the maximum number of soldiers was reached, c. 5,500 soldiers would have been present and accordingly c. 5,500 *vicus* inhabitants (Table 5.17; Chapter 4). Sommer (1984; 1991) even suggests that the number of people living in the *vicus* might have been twice the number of soldiers. Although only small sections of the *vici* in the Lower Rhine Delta have been excavated these mainly uncovered extensively used areas, often interpreted as gardens, thus leaving only a few hectares per *vicus* for dwellings (e.g. Hazenberg, 2000; Ploegaert, 2006; Vos *et al.,* 2012). Therefore, we think that each *vicus* only consisted of a few dozen houses. Such a small number of dwellings does not match very large garrisons and presumably implies that

Table 5.16 The maximum number of reconstructed rural settlements-units per region and location north and south of the river Rhine.

	West	Central	East	Total
Early Roman period (AD 40-69)				
Northern dunes	18	-	-	18
Northern levees	7	18	32	57
Southern dunes	18	-	-	18
Southern levees	11	22	73	106
Total	*54*	*40*	*105*	***199***
Middle Roman period (AD 70-140)				
Northern dunes	18	-	-	18
Northern levees	7	18	32	78
Southern dunes	36	-	-	18
Southern levees	22	44	146	158
Total	*83*	*62*	*178*	***323***

our assumption of 350 soldiers per fort and an equal number of people living in the surrounding *vicus* is rather a maximum estimate than an under-estimate. Still, if indeed 5,500 soldiers were (temporarily) present in both periods, the military food demand would have increased by a factor 1.5 in both periods. In that case, the landscape could probably still provide sufficient supply of wood and food in the Early Roman period, but the rural population would have been too small to feed this population, both in terms of cereals and meat. In the Middle Roman period both the landscape and the labour force provided by the rural population would probably have become restricting.

Another uncertainty is the ratio in the consumption of cereal/plant food and animal food, and the species consumed. The rural and military population may have relied on a larger portion of other plant-based categories or on animal products obtained through hunting or fishing than assumed in our model. For example, the fish traps, tanks and fish remains unearthed at or near military sites in the research area show that fish was caught and eaten by the soldiers (Beunder, 1990; Esser *et al.*, 2007; Lange, 2012; Van Regteren Altena and Sarfatij, 1994a; idem b; Van Rijn, 1993; idem, 2013). Clearly, fish was a source of protein. However, fish can never have been responsible for more than a small portion in the daily needs of the Roman soldiers. And contemporary rural settlements, even when located near rivers, brooks or the sea, do often not yield any indication for fishconsumption, a phenomenon that cannot be explained by excavation methods (e.g. Groot, 2009). Also, hunting in the Roman army was severely restricted. The consumption of sheep/goat, chicken and pig has been attested in both rural settlements and military installations in our research area but never in large quantities (Cavallo *et al.*, 2008a; Groot, 2008; Groot *et al.*, 2009; Groot and Kooistra, 2009). And the ratio of land required for grazing and the calorific output of sheep and goat are negative compared to that of cattle; very large herds and amounts of land would be necessary for the same output of calories.

But even when the meat rations of the soldiers are reduced, the number of extra herds per settlement-unit would on average have been too large in terms of labour availability. For xample, if only c. 10% of the diet consisted of meat and meat products from cattle only, so almost half the amount used in our model, the number of extra herds per settlement-unit would have been about one extra herd of 50 heads in the Early Roman period and c. two herds in the Middle Roman period (see also section 5.4.2). This still seems too large to manage for one settlement-unit.

Table 5.17 The maximum number of soldiers and vici inhabitants per period per region.

	West	Central	East	Total
Early Roman period (AD 40-69)				
Forts (N)	3	4	3	10
Vici (N)	0	0	1	1
Number of soldiers	1500	2000	2000	5500
Number of vici inhabitants	0	0	1000	1000
Total population	*1500*	*2000*	*3000*	***6500***
Middle Roman period (AD 70-140)				
Forts (N)	3	4	3	10
Vici (N)	3	4	3	10
Number of soldiers	1500	2000	2000	5500
Number of vici inhabitants	1500	2000	2000	5500
Total population	*3000*	*4000*	*4000*	***11000***

Also, it is assumed that the yields of the arable fields and grasslands, and the health of the herds were optimal and constant. However, conditions in nature are not constant and optima rarely occur. Hail storms, diseases and pests, periodic flooding and droughts would frequently have caused harvest failure and thereby regularly have reduced the potential local surplus production. In our opinion, soil exhaustion was not likely to have influenced production in the delta as fertile sediment was regularly provided by flooding, even on the high levees (Berendsen and Stouthamer, 2001).

Then again, the archaeological record shows the presence of cavalry (Glasbergen and Groenman-van Waateringe, 1974; Chorus, 2013) and horses in rural settlements (Cavallo *et al.*, 2008b; Goossens, 2010; Van Dijk, 2008a; idem, 2008b; Vos and Lanzing, 2000). In addition, pack animals, like mules, may also be assumed to have been present. The extra needs of these non-food animals in terms of fodder and housing have been left out of our calculations but put an extra pressure on the landscape.

The ration of cereals of a cavalry-soldier with horse and servant(s) obviously differed from the ration of an infantry soldier. According to Polybius, who lived in the 2nd century BC, a Roman cavalry-soldier received two Attic *medimni* of wheat a month (equal to c. 2.5 kilo per day; Erdkamp, 1998) and seven *medimni* of barley (equal to c. 8.8 kilo per day). Hereby, it is assumed that the wheat was consumed by the soldier and his servant(s) while the barley was consumed by the horse and pack animals. An auxiliary cavalry-soldier received less: 1 1/3 Attic *medimni* per month (c. 1.7 kilo of wheat per day), and 5 attic *medimni* per month (c. 6.3 kilo barley per day; Polybius 6.39).

Evidence for the presence of cavalry-units is only established for the forts in Vechten, Utrecht and Valkenburg (section 5.2.2.2). Due to the comparable size of the forts in Valkenburg and Utrecht, it it is not plausible that more than an half halve *ala quingenaria* (8 *turmae*, each consisting of 16 horsemen) at the most was stationed in the fort in Utrecht as well. However, the fort in Vechten was larger and might have housed a larger cavalry-unit. To feed the horses and other pack animals of half an *ala quingenaria* c. 600 tons of barley would have been needed per year (8 *turmae* x 16 horses x 6.3 kilo barley x 365 days). To grow this amount of barley, 7.5 km^2 arable land is necessary per half *ala quingenaria* or 15 km^2 including fallow land (Appendix C: 3.3.2). Considering the required space for stables, however, it is likely that fewer soldiers were stationed in the forts with cavalry units than in the forts without cavalry. However, the ration of cereals for a horse is much larger than that for a soldier (Polybius 6.39). Therefore, when it comes to the supply of cereals, soldiers and horses are not interchangeable in a cereal supply-model.

In our model, in the Early Roman period there are some rural settlement-units that could potentially cultivate extra arable land, both in the western coastal region and in the eastern river region (i.e. 5.2 km^2 in total; Table 5.14). In the Middle Roman period, this is only the case in the eastern region, i.e. 8.4 km^2 (Table 5.14). Since 7.5 km^2 was already required to grow barley for one half *ala quingenaria*, there are not enough agrarian settlements in our research area to supply at least three *alae quingenariae* with enough barley for horses and pack animals. Thus, this barley must have been imported. The eastern river region was part of the relatively densely populated and intensively exploited *civitas Batavorum* (Chapter 4). Research by Vossen and Groot (2009) argued that farmers of the entire *civitas Batavorum* must have been able to supply enough barley for the Roman army in the Dutch delta, including horses.

Altogether, we assume that the numerous parameters will not all have been estimated either too high or all too low; some will be estimated too high and others too low. We believe that the total results of our calculations do not change significantly by various changes in parameters. This means that the order of magnitude of the estimated demand and supply will remain the same, so that the conclusions of section 5.4.1 and 4.2 will be upheld.

5.4.4 Provisioning of the Roman army

In the opinion of the authors, the rural population in the Lower Rhine Delta may have been much more involved in the provisioning of the Roman army between AD 40 and 140, especially for wood and cereals, than has been assumed until now. For meat supply, the picture is less clear. The rural settlements in the central part of the Rhine-Meuse delta do show changes in settlement structure, storage capacity and animal husbandry, proving that they were already integrated into a larger economical framework in the early phase of military presence (Groot *et al.,* 2009; Heeren, 2009). Apparently, the arrival of the Roman army influenced the rural settlements to change their economy and intensify their production, perhaps by putting pressure on and taxing the rural population. However, the local provisioning of food had to be combined with import over long(er) distances, just as in other parts and other periods of the Roman Empire, for example Scotland (Hanson, 2007), England (Thomas, 2008), and Central Jordan (Parker, 2006).

The provisioning with timber and fuel seems to have been much more a solely military matter that was carried out by the soldiers themselves. Such activities would have posed too much of a logistical problem for the rural population, certainly at periods of heightened activities, for example the transport of large quantities of wood from alder wetlands to the places of construction. For the road and river infrastructure along the river Rhine of AD 123/125 oak was imported. The employment of the rural population in the wood winning did probably not start until the development of alder copses in the Middle Roman period.

5.5 Conclusion

The estimates of the demand and supply of the Roman army in the western Lower Rhine Delta with wood and locally produced food during the first one hundred years after the arrival of the army shows that the landscape in the Early Roman period (AD 40-70) could in theory meet the total demand of the total population in the area and posed no limit. The required space for forestry, arable farming and animal husbandry was available and did not conflict. However, because of a rising population the pressure on the landscape increased in time. From the end of the 1st century

AD onwards, the landscape may have posed an upper limit on the availability of local resources and thereby the local production.

The calculations show that nearly all wood, for both construction and fuel, could be gathered locally during the whole research period. This corresponds to the archaeological record. The employment of the rural population in the wood winning did probably not start until the development of alder copses in the Middle Roman period.

In addition, the total rural population, even estimated at a minimum, was also able to produce enough surplus cereals, e.g. emmer and barley, to fulfil the demand of the Roman army and its associates for these cereals (assuming that only 50% of the total military demand for cereals was derived from cereals that could be produced in the local surroundings). Cereal deficits in the central and western region could be supplemented by surplus yields from the eastern region. However, spelt wheat and bread wheat, other components of the military diet, were not cultivated locally and had to be imported.

Meat supply for the Roman army most probably did form a problem. The rural settlements would have to keep implausibly large cattle herds for which manpower was also lacking. Therefore, it seems likely that the Roman army combined local provisioning with extra-regional supply and long-distance transport.

Overall, the local population was probably much more involved in the provisioning of the Roman army in the Lower Rhine Delta between fort Vechten and the North Sea, especially for cereals, than hitherto assumed. Therefore, this study is a step forward in identifying the carrying capacity of the natural landscape and the logistical organisation concerning the provisioning of the Roman army in the Rhine delta.

6 Late Holocene lowland fluvial archives and geoarchaeology: Utrecht's case study of Rhine river abandonment under Roman and Medieval settlement

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6.1 Introduction

Rivers provide fresh water, open landscapes and transport routes for humans and as such have been repeatedly occupied environments through all archaeological periods (Hill, 2014). The relations between fluvial archives and their archaeological content have shown major changes over time (e.g. Ferring, 1986; Brown, 1997). Important differences on the Eurasian continent occurred between the eras of and preceding the Neanderthals (Early and Middle Paleolithic of the Pleistocene interglacials and glacials; e.g. Roebroeks, 2001; McNabb, 2007; Cohen *et al.,* 2012a; Bridgland and White, 2015), the times of Home Sapiens hunter-gatherer subsistence (Late Paleolithic and Mesolithic of the Lateglacial and Early Holocene; e.g. Kelly, 1983; Louwe Kooijmans *et al.,* 2005), the subsequent Neolithic revolution towards agricultural subsistence which enhanced permanent settlements (Middle Holocene; e.g. Butzer, 1970; Van Andel and Runnels, 1995; Bonsall *et al.,* 2002; Turney and Brown, 2007), and the Late Holocene with increasingly developed catchment deforestation, growing population and urbanization, expanding trade and accelerating cultural exchange (e.g. Kaplan *et al.,* 2009; Gates, 2011). With growing human presence and its impact in the catchments and rivers in the hinterland, especially in the last few millennia river discharge regimes changed as well, with larger fluxes of sediment supplied to the lowlands (e.g. Hoffmann *et al.,* 2007). Further river-engineering changes such as the construction of dikes downstream and dams upstream caused the sedimentation regimes to change once more (e.g. Hesselink *et al.,* 2003; Hudson *et al.,* 2008; Syvitski *et al.,* 2005; 2009).

Rivers are notoriously effective at reworking their past fluvial archives, eroding and redepositing their alluvium including the archaeological materials contained here (e.g. Brown, 1997). This is particularly true for valley reaches that over longer time intervals produce terrace sequences and for deposition in active channels. These processes create surfaces on which archaeology can accumulate afterwards and in such cases fluvial geomorphological patterns are informative for archaeological site distribution, especially on neighbouring terrace edges (e.g. Howard and Macklin, 1999; Bettis *et al.,* 2008). In the lower delta-plain reaches of rivers, however, the downstream control of post-glacial sea-level rise and wide glacial-inherited valleys have caused extensive Late Holocene records to have become preserved and accessible for geological and archaeological research. These areas can be especially rich in well-preserved archaeological finds (e.g. Edelman, 1950; Willems, 1986; Ferring, 1992). These finds are located in overbank deposits, in the tops of bars and not in the least, in deposits from abandonment and post-abandonment stages. In the latter case the alluvial ridges provide subtle high grounds in an otherwise regularly flooded plain.

In most deltas worldwide, including those of classic civilization centres such as Mesopotamia (e.g. Jacobsen, 1995; Wilkinson, 2000), the Egyptian Nile Delta (e.g. Coutellier and Stanley 1987; Macklin *et al.,* 2015; Trampier *et al.,* 2013; Pennington *et al.,* 2015; Pennington and Thomas, 2016), the Maya Lowlands (e.g. Von Nagy, 1997; Gunn *et al.,* 2000; Liendo *et al.,* 2014; Nooren *et al.,* 2014) and the Indus (e.g. McIntosh, 2008; Giosan *et al.,* 2012; Syvitski *et al.,* 2013), besides the modern active river branches multiple former river branches of Late-Holocene age have been identified. These are the parts of fluvial reaches where long-sustained coeval geomorphological and human activity has taken place, creating spatially extensive and continuous fluvial archives of alluvial ridges with a very rich embedded archaeological record. In these areas rivers continuously changed their course and networks due to avulsion, creating new and abandoning older channels. In addition in these areas cultures changed, and distinct cultural periods emerged and succeeded. The dating of such periods is often very precise, sometimes with an uncertainty of a few years only, and outperforms that of sites dated exclusively with geological dating methods. Both from an archaeological and geomorphological perspective deltaic lowlands therefore provide rich archives for the study of the interaction between river processes and human occupation.

The study of human-fluvial landscape interactions requires an interdisciplinary approach integrating geological and archaeological datasets derived from fluvial archives. In the present study we exemplify this for the case of The Netherlands, where the rise of the Roman/Medieval city of Utrecht coincided with a shifting bifurcation and changing channel dimensions and meander lengths during a 1,000-yr abandonment phase of the main river in the Lower Rhine Delta.

Avulsion is a principal process in the creation of new channels and the abandonment of existing channels in deltas and fluvial plains. It is a process that is seldom observed on a human time scale since it usually takes several human generations for the new channel to fully capture the water discharge (Jones and Hajek, 2007). Over the last 30 years research on avulsions in lowland settings mainly has focused on newly formed channels and related sedimentary products such as crevasse splays and avulsion belts (e.g. Smith *et al.,* 1989; Smith and Perez-Arlucea, 1994; Stouthamer, 2001; Slingerland and Smith, 2004; Makaske *et al.,* 2007), and on the quantification of avulsion frequencies, which most frequently is based on dating abandoned channels in order to identify channel relocation events (e.g. Törnqvist, 1994; Stouthamer and Berendsen, 2000; Makaske *et al.,* 2002; Stouthamer, 2005; Fontana *et al.,* 2008).

The pace of avulsion processes strongly varies depending on constraints such as basin configuration, local and regional gradients, and dynamics of bends and in-channel bars (e.g. Mackey and Bridge, 1995; Jones and Schumm, 1999; Slingerland and Smith, 2004; Stouthamer, 2005; Kleinhans *et al.,* 2013). Studies of the Dutch Rhine-Meuse delta, an exceptional region because of its complete coverage of the Holocene avulsion history including avulsion duration (e.g. Berendsen and Stouthamer, 2001; Stouthamer and Berendsen 2000; Gouw and Erkens, 2007; Stouthamer *et al.,* 2011; Toonen *et al.,* 2012), show that new and old channels often co-functioned for a few hundred years (Stouthamer and Berendsen, 2001).

Younger secondary channels developed 'relatively rapidly' (Jones and Schumm, 1999), but the majority of the discharge remained routed through the older course. The larger channels were the longest-lived courses which functioned as relatively conservative trunk channels (Stouthamer *et al.,* 2011). In the few cases that a major avulsion led to full abandonment of a trunk channel in the Rhine-Meuse delta, the process took a long time to complete (Stouthamer and Berendsen, 2001; Toonen *et al.,* 2012). One reason that large and old main channels did not easily become completely abandoned, is that fully plugging a former trunk channel demands considerable amounts of bed sediment to be trapped at its entrance. This not only takes time, but also requires sustained delivery of this sediment by the flow of water that is diverted over a bifurcation at the avulsion node. The instable morphodynamics of a bifurcating river causes the quantities of water and sediment delivered to the competing branches to oscillate (Kleinhans *et al.,* 2008; 2011; 2013). This causes alternating phases of deposition (plugging, narrowing) and erosion (deepening, re-widening) of the channel, never closing either of the two branches, a situation that can persist for many hundreds to a few thousands of years. During this time interval the sedimentary signals of discharge loss and branch abandonment become visible over many meander wave lengths downstream in the abandoned branch, i.e. over reaches of tens of kilometres. The combined down- and upstream feedback effects of multiple bifurcations of different age occurring concurrently in the delta cause further complexity of the abandonment mechanisms of main branches.

The Utrecht case study demonstrates the slow pacing and staged natural river development over the full duration of abandonment, coincident with intensifying human occupation. The analyses focus on a 1,000-year period, making maximum use of the tight age control enabled by geoarchaeological dataset integration (see the rich dataset accompanying this chapter). This allowed us to quantify changes in river dimensions and meander style and to provide discharge estimates for successive stages of the abandonment phase. River researchers benefit from the interdisciplinary incorporation of geoarchaeological data since it leads to age-control on the phasing, and archaeologists benefit since it enables them to develop a more detailed insight in autogenic landscape change. This in turn creates awareness of situations in which inhabitants in the past actively must have countered unwanted change or in which people opportunistically seized opportunities provided by autonomous river development. In this manner this interdisciplinary approach enables more complete explanations of the timing and duration of successive patterns of human settlement observed along the former river.

6.2 Setting of the study area

6.2.1 Abandonment of the Utrecht Rhine

A major avulsion case in The Netherlands in the last 3,000 years is marked by the abandonment of the Kromme Rijn and Oude Rijn branch in the northwestern part of the Rhine Delta (Fig. 6.1). This branch, running through Utrecht and debouching into the North Sea at Katwijk, is the main artery of the Utrecht river system (e.g. Berendsen, 1982; Berendsen and Stouthamer, 2000). Names, identification numbers and dates for the period of sedimentary activity of the various channel belts (ch.b.) that compose the Utrecht river system were introduced by these authors (updated Cohen *et al.,* 2012b) and are followed here. This long-lived system groups multiple partly successive channel belts (Fig. 6.2), that began functioning in the Middle Holocene, some 6,500 years ago (Hijma and Cohen, 2011), and had become the single main Rhine channel by 5,000 cal BP (Stouthamer and Berendsen, 2000; Cohen *et al.,* 2012b). Due to a series of upstream avulsions the former Rhine trunk channel gradually lost discharge to the new distributaries Waal, Lek and IJssel during the 1st millennium AD (Fig. 6.1), i.e. beginning in the Roman Period and completing in Medieval times.

The abandonment phase is well registered in the preserved meander morphology of the last stages of activity as well as in the sedimentary build-up of its channel fill, albeit that large parts of the channel belt nowadays are built upon. In the 12th century AD, when dikes were being placed along the larger channels, the Kromme Rijn and Oude Rijn branch had reduced to a very minor channel

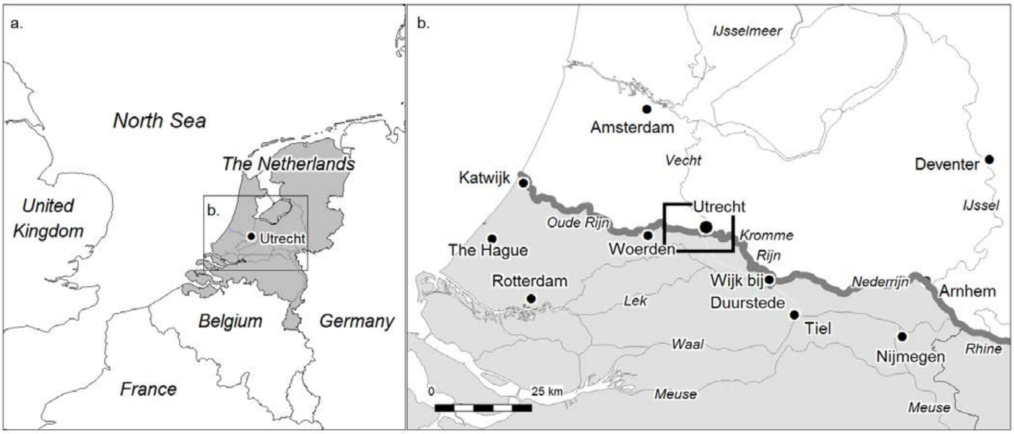


Figure 6.1 Location of the study area (box): a. in the central part of the Netherlands, b. near the city of Utrecht along the river Kromme Rijn – Oude Rijn (box); shaded area is the Roman province of *Germania Inferior* at end of the 1st century AD.

in terms of carrying discharge (Berendsen, 1982). While losing discharge the branch maintained its importance as a transport route. Furthermore its relatively high and inhabitable levees formed a dry land zone running through otherwise swampy surroundings which were reclaimed by drainage during the Middle Ages (e.g. Borger and Ligtendag, 1998). To enable land reclamations in the flood basins the silted-up Kromme Rijn-Oude Rijn channel was disconnected from the Nederrijn channel in AD 1122 by the construction of a dam at the avulsion node at Wijk bij Duurstede (Dekker, 1980). This meant that the Rhine branch through Utrecht, unlike the other water carrying rivers of that time, was not to be embanked. This historical event of upstream dam construction marks the end of the abandonment process of the Oude Rijn branch as presented in this chapter.

Throughout the abandonment phase, settlement on and utilisation of the Kromme Rijn and Oude Rijn alluvial ridge concurred with sedimentary activity. During the Roman occupation (12 BC – AD 450; *Germania Inferior*) the branch was used as a main transport corridor and eventually functioned as a military border, the *Limes*, until AD 270 (Haalebos, 1997b; Polak, 2009; Sommer, 2009; Van Dinter 2013). During the Early Middle Ages (AD 450-1050) it continued to function as a major trading route (Van Es and Verwers, 2010; Dijkstra, 2011; Jansma and Van Lanen, 2016; Van Lanen *et al.,* 2016). This abundant habitation history has left a rich archaeological record which complements the sedimentary record of the abandonment phase.

A long tradition of archaeological research exists that also includes reconstruction of former river positions, mainly because of the relations between the river, its alluvial ridge and the layout of this part of the Roman *Limes*. Results are available for the city of Utrecht and its surroundings (e.g. Ozinga *et al.,* 1989; Polak and Wynia, 1991; Polak *et al.,* 2004), for the area further downstream along the Oude Rijn (e.g. Haalebos, 1977; Blom and Vos, 2008; Chapter 2), and for areas in the vicinity of the upstream avulsion node (at Wijk bij Duurstede; Figs. 6.1, 6.2), including the site of Early Medieval trade centre *Dorestad* (e.g. Van Es and Verwers, 1980; 2009; 2010; 2015; Dekker, 1983; Van Es, 1984; 1990; 1994; Hessing and Steenbeek, 1990; Verwers, 1994; M. Dijkstra, 2004; Sier *et al.,* 2004; Dijkstra, 2012; Williams, 2010; 2013; Kosian *et al.,* 2016). *Dorestad* was one of the principal ports of the Carolingian realm in northwestern Europe (AD 725-900; *Annales Bertiniani,*

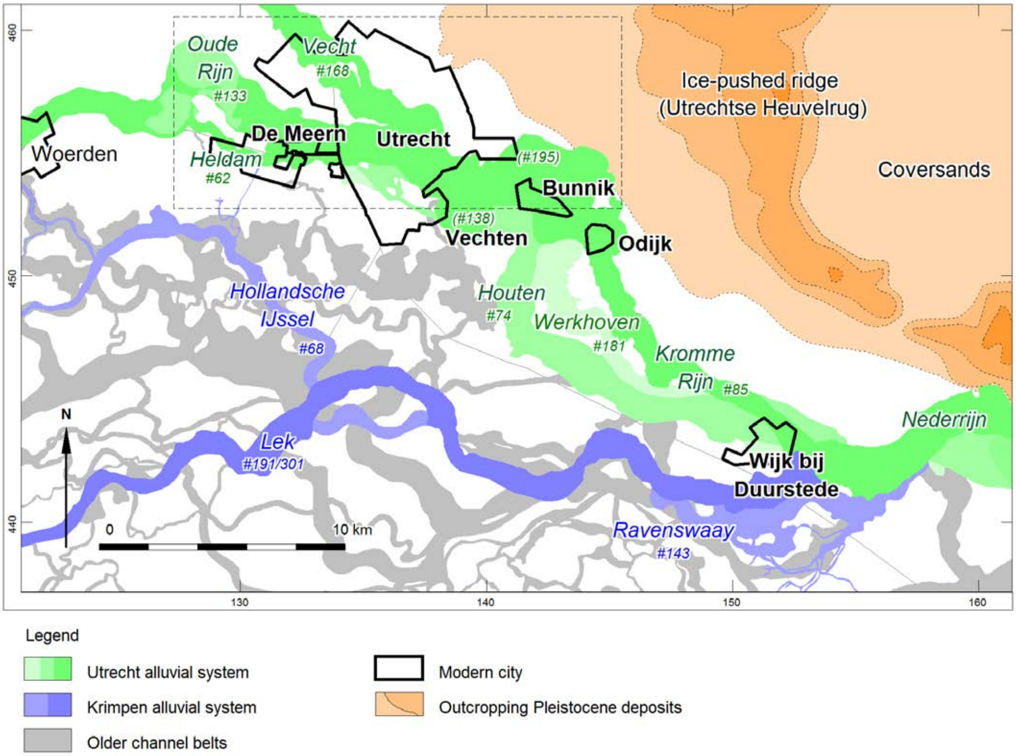


Figure 6.2 The palaeogeographical situation between Wijk bij Duurstede and Woerden during the Roman and Medieval periods (source data: Cohen *et al.* (2012). Older phases are indicated in lighter colour tones. The box indicates the study area (Fig.6.4).

Annales Fuldenses, Annales Xantenses). During the last two decades intensified (geo)archaeological research especially in and around Utrecht has generated new data regarding river activity and the settlement history of the channel belt (e.g. Graafstal, 2002; Nokkert *et al.,* 2009; Hoegen, 2013; Aarts, 2012; Den Hartog, 2009a; 2010; 2013a; 2013b). However, the geomorphological development of the Roman and Medieval fluvial landscape, the pacing and sedimentological process knowledge of channel abandonment and the cultural response to changes in modes of river activity still remain to be explored.

This study makes use of the enriched geological-geomorphological and archaeological datasets that exist for the Oude Rijn and Kromme Rijn channel belt from the sources cited above. These data enabled a detailed reconstruction of the abandonment phase of the Oude Rijn and the analysis of anthropogenic interaction with the river environment.

6.2.2 Avulsion history at delta scale

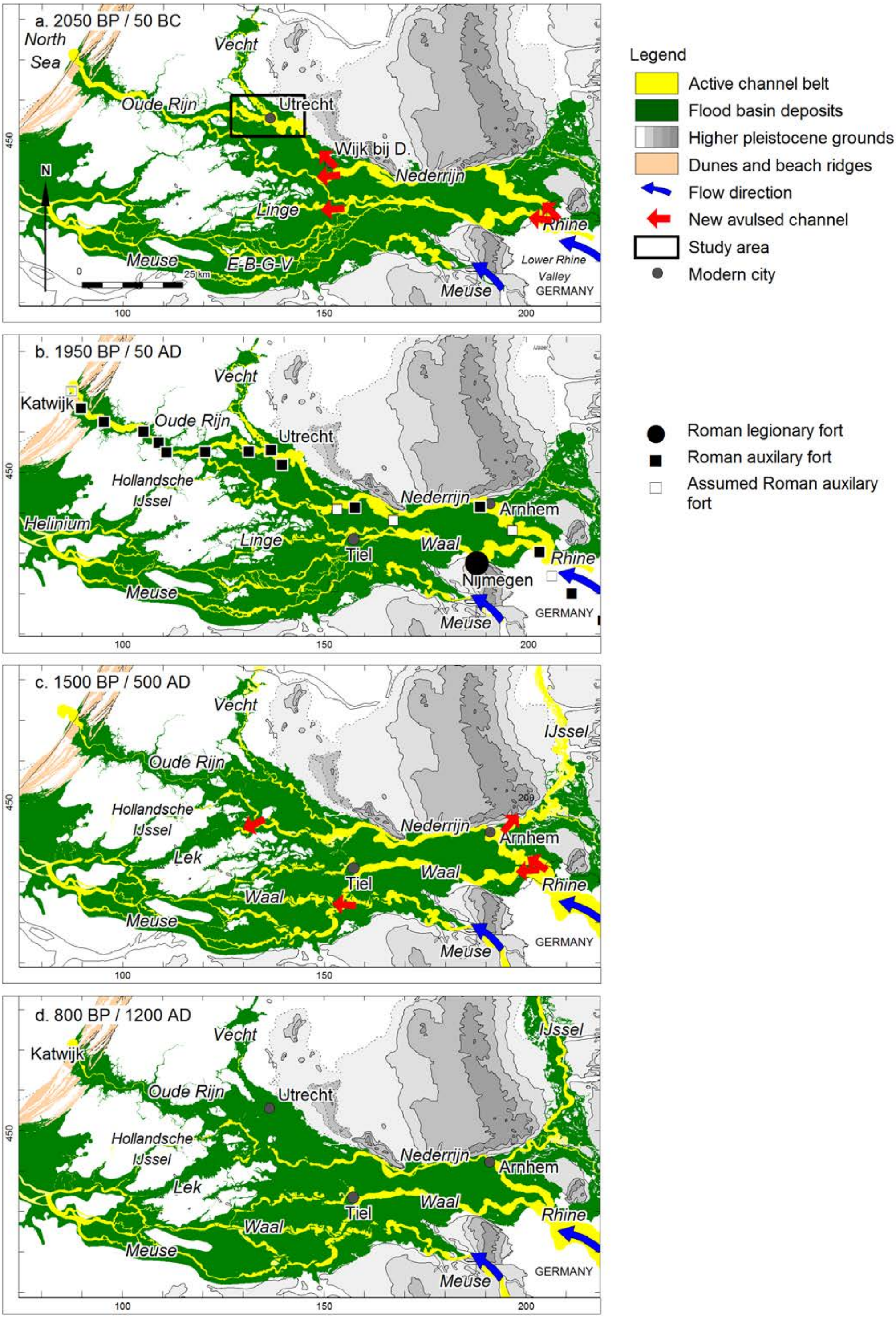
The study area is situated in the northwestern part of the Rhine-Meuse delta and centres around the city of Utrecht (Fig. 6.2). Downstream of Utrecht, the Oude Rijn (ch.b. #133) was active since ~5730 ^{14}C yr BP (6500 cal BP, ~4500 BC; dating confirmed at multiple locations). The Utrecht channel belt traverses an area north of the Late Glacial and Early Holocene Rhine palaeovalley, with a dominantly sandy Pleistocene subsurface. To the east of the study area, Middle Pleistocene sand outcrops as ice-pushed ridges from the penultimate glaciation (Figs. 6.2 and 6.3; Utrechtse Heuvelrug). The study area overlies outwash deposits from that same glaciation (Saalian, 150 ka), which were reworked by the Rhine during part of the last glacial (Middle Weichselian, 60-35 ka) and afterwards were blanketed with cover sands (35-12 ka; Busschers *et al.,* 2007). At a distance from active rivers a peat cover developed during the Middle Holocene as an effect of relative sea-level rise and seepage received from the ice-pushed ridge (Cohen, 2005; Van Loon *et al.,* 2009; Van Asselen, 2011). The avulsions giving rise to the Utrecht channel belt system invaded and dissected this peat-on-cover-sand landscape along the northern rim of the Rhine-Meuse delta (Berendsen, 1982; Berendsen and Stouthamer, 2001). Availability of Pleistocene sand at shallow depth (on the shoulder of a palaeo-valley) and constant groundwater seepage in addition to Rhine discharge (hydrological connection to flanking topography) are factors explaining the well-developed meander morphology in the study area. The average thickness of the Holocene flood-basin deposits is ~ 1 m directly east of the city of Utrecht, increasing to roughly 4 m west of Utrecht near De Meern (Fig. 6.2).

Upstream of Utrecht, three channel belts successively have fed the Oude Rijn, each diverging from the avulsion node at Wijk bij Duurstede and all converging at Utrecht (Berendsen, 1982). In chronological order these are, the Werkhoven (ch.b. #181), Houten (ch.b. #74), and Kromme Rijn (ch.b. #85) channel belts (Fig. 6.2; Berendsen, 1982, 1990). By ~2500 ^{14}C yr BP the Kromme Rijn and Oude Rijn had become the main Rhine channel (Cohen *et al.,* 2012b: ch.b. #74 and #85). In the city of Utrecht the Vecht channel belt (ch.b. #10 and #168) bifurcates northward. West of Utrecht the Heldam (#62) channel belt over a distance of ~ 5 km runs parallel to the main Oude Rijn (#133) channel belt. The sedimentology of the Oude Rijn channel belt is modestly influenced by tides from about 10 km downstream of Utrecht (Martinius and Van den Berg, 2011), whereas in Roman times the tidal influence was felt along the channel until Woerden (Chapter 2). Our study area begins immediately upstream of these tidal-influenced reaches.

During the 2nd millennium BC the Oude Rijn branch was the only permanent channel connecting the inland delta plain to the North Sea (Berendsen and Stouthamer, 2000; Gouw and Erkens, 2007; Gouw, 2008; Stouthamer *et al.,* 2011) and at that time essentially carried the full discharge of the Rhine. Due to upstream avulsions the Oude Rijn consecutively lost part of the Rhine discharge from the 1st millennium BC onwards. Discharge was first lost around 850 BC due to the formation of the river Vecht (Fig. 6.3a; Törnqvist, 1993; Weerts *et al.,* 2002; Bos *et al.,* 2009, Cohen *et al.,* 2012b: ch.b. #10 and #168; ~2800 ^{14}C yr BP), which resulted from an avulsion that occurred at Utrecht (Fig. 6.2). However, given the size of the Vecht branches and its lake deltas this constituted a relatively small amount of discharge loss (Bos *et al.,* 2009; Bos, 2010).

In contrast, the discharge decrease induced by a later series of upstream avulsions near Wijk bij Duurstede was much larger and ultimately led to the abandonment of the Utrecht river system (cf. Berendsen, 1982) in favour of the Krimpen river system that still is functioning today (Figs. 6.2, 6.3b). Initially, part of the water flow of the Nederrijn drained into the Hollandsche IJssel (Fig. 6.2; Stouthamer, 2001; Cohen *et al.,* 2012b: Ravenswaay, ch.b. #143: 2200-1500 ^{14}C yr BP; 2220 ± 35 BP (GrN-8708), but since ~ 1950 BP increasing amounts of water were discharged through the Lek (ch.b. #191/301: 1950 ± 30 BP (GrN-8707), 1805 ± 50 BP (GrN-7577)).

Figure 6.3 (right) Palaeogeographical situation of Rhine-Meuse delta in a. 2050 BP (~50 BC), b. 1900 BP (~AD 100), c. 1500 BP (~AD 550), d. 800 BP (~AD 1150) (after Cohen *et al.,* 2012; Roman forts: after Polak, 2009; E-B-G-V = Echt-Bruchem-Gameren-Velddriel system.).


a. 2050 BP / 50 BC
North Sea
Vecht
Oude Rijn
Utrecht
Wijk bij D.
Nederrijn
Linge
Rhine
Meuse
E-B-G-V
Lower Rhine Valley
GERMANY
b. 1950 BP / 50 AD
Katwijk
Hollandsche IJssel
Helinium
Arnhem
Tiel
Waal
Nijmegen
c. 1500 BP / 500 AD
IJssel
Lek
d. 800 BP / 1200 AD
Legend
Active channel belt
Flood basin deposits
Higher pleistocene grounds
Dunes and beach ridges
Flow direction
New avulsed channel
Study area
Modern city
Roman legionary fort
Roman auxilary fort
Assumed Roman auxilary fort

In the course of time, large changes in river pattern upstream of Wijk bij Duurstede also affected the water discharge of the Utrecht system (Fig. 6.6.3b-d). The Nederrijn already started to receive less water just before the Roman Period, because an avulsion occurred near the present day city of Tiel (Fig. 6.3b; Cohen *et al.,* 2012b: Linge, ch.b. # 97: 2160-643 ^{14}C yr BP; 2210 ± 40 BP (UtC 1482); 2160 ± 60 BP (UtC 1717), 2035 ± 50 BP(GrN-8371). In the Late Roman Period, another avulsion occurred close to Tiel, further downstream along the Waal (Fig. 6.3c). This resulted in an increased discharge of the Waal channel belt downstream of Tiel (ch.b. #174: since 1625 ^{14}C yr BP), the formation of a connection with the river Meuse and the ending of the Est-Bruchem-Gameren-Velddriel system (Cohen *et al.,* 2012b; start of Waal: 1655 ± 50 BP (GrN-13504) and 1600 ± 50 BP (UtC-1899)). Furthermore, the river Gelderse IJssel came into existence in the Early Medieval Period (Fig. 6.3c; Cohen *et al.,* 2009; 2012: ch. b. #50: since ~1700 BP; Makaske *et al.,* 2008; Groothedde, 2010, 2013), thereby further reducing the discharge of the Nederrijn downstream of Arnhem (Fig. 6.3).

Different perceptions of the magnitude of discharge carried by the Utrecht Rhine around the time of its damming in AD 1122 have been published. Some authors have postulated that the damming only put an end to an already on-going natural process of abandonment that had begun in Roman times (e.g. Vink, 1954; Berendsen, 1982; Kleinhans *et al.,* 2013: suppl. information). Others, mainly archaeologists and historians, until recently assumed that the Lek became the larger Rhine branch after the 9th century only, and inferred that the Kromme Rijn was a fairly broad waterway at the time of the 12th century damming (e.g. Verwers, 1994; Van Es and Verwers, 2009). Nonetheless the effect of the changing delta river network during the Middle Ages nowadays is more and more considered also in archaeological studies (e.g. Kosian *et al.,* 2013; Groenewoudt *et al.,* 2016; Kosian *et al.,* 2016).

6.2.3 Settlement history of Utrecht and its surroundings

The history of the city of Utrecht is well known and has been extensively documented (e.g. Van Asch van Wijck, 1838; De Bruijn, 1994; 2008; Broer and De Bruijn, 1995; Stöver, 1997; Van Rooijen and Wynia, 1998; Van Rooijen, 1999; 2010; De Groot, 2000; Van Vliet, 2000a, 2000b, 2002; Renes, 2005; De Kam *et al.,* 2014). The standard Dutch archaeological time periods relevant for this chapter are shown in Table 6.1. During the 1st century AD a Roman auxiliary fort was erected along the river Oude Rijn, guarding the bifurcation with the river Vecht (Fig. 6.3b; Ozinga *et al.,*. 1989; Montforts, 1995; Chapter 2). From the 7th century AD onwards, this fort became the residence of the Frankish settlers, initially in ~ AD 690 led by the Anglosaxon missionary Willibrord (De Bruin, 1994; Stöver, 1997). Utrecht became a major ecclesiastical centre because of its episcopal chair and developed into an important Medieval political and trade settlement. After the damming of the river Kromme Rijn at Wijk bij Duurstede in AD 1122 the city lost its riverine supply route, which was solved by digging a canal towards the Lek/Hollandsche IJssel soon afterwards (Dekker, 1980, 1990). In this manner riverine translocation and trade was preserved and the city continued its status as central regional market in the Medieval economy (Van Vliet 2002a; 2002b).

Two other Roman forts, *castella*, were present in the immediate surroundings of Utrecht directly along the river, the first 5 km upstream of Utrecht near Vechten and the second 9 km downstream in De Meern (Figs. 6.2, 6.3b). These fortifications were part of a chain of forts built on the left bank of the Rhine between Vechten and the North-Sea coast at Katwijk around AD 40 (Van Es, 1981; Bechert and Willems, 1995; Haalebos, 1997b; Polak, 2009). By the end of the 1st century AD, this chain became the northwestern frontier of the Roman Empire, the so-called *Limes* (Polak, 2009; Chapter 2). The *castellum* near Vechten was erected on the outer bank of the river Rhine during an

Table 6.1 Standard subdivision of the Roman and Medieval periods in the Netherlands (Anonymous, 1992); * = dynasty period.

Late Iron Age	250 – 12 BC
Early Roman period	12 BC – AD 70
Middle Roman period	AD 70 – 270
Late Roman period	AD 270 – 450
Early Medieval period	AD 450 – 1050
*Merovingian period**	*AD 447 – 751*
*Carolingian period**	*AD 751 – 987*
Late Medieval period	AD 1050 – 1500

earlier campaign shortly after the start of the 1st century AD (Polak and Wynia, 1991; Zandstra and Polak, 2012). This fort is larger than the other forts in the area and therefore appears to have served as a command centre of the *Limes* segment west of the legionary fortresses at Nijmegen and Xanten (Germany). In the late 2nd century it was most likely larger than the other forts in the area and measured 2.6 ha – versus 1 ha for the other forts along the Oude Rijn. The Roman fort in De Meern was situated at the junction of the alluvial ridges of the Oude Rijn and the Heldam channel belts (Jongkees and Isings, 1963; Kalee and Isings, 1984; De Jager, 2000; Van der Gaauw and Van Londen, 1992; Chapter 2). The *Limes* road, built at the end of the 1st century AD to connect the chain of forts over land, was mainly situated on the Heldam alluvial ridge (Haarhuis, 1997; 1999a; 1999b; 1999c; Graafstal, 2002; Luksen, 2010).

The Roman *castella* lost their importance when the northwestern part of the *Limes* in the Rhine-Meuse delta was evacuated (AD ~260-270). The Roman reign in The Netherlands (*Germania Inferior*) ended in ~AD 405-406 (Van Es, 1981; 1994). The main difference between the Utrecht, Vechten and De Meern forts is that the Utrecht locality regained importance in Medieval times, whereas the others lost institutional use.

In AD 723 Charles Martel, the Prince of the Franks and Mayor of the Palace, donated the strongholds of Vechten and Utrecht and their surroundings to the Church of Utrecht (*Diplomata Belgica* I, nr. 173, 175 and 176). Archaeological information about the Early Middle Ages from the surroundings of Utrecht is scarce (Haarhuis and Graafstal, 1993), although recently excavations have begun in these surroundings to reveal the settlement history and landscape development for this period (e.g. Nokkert *et al.,* 2009; Den Hartog, 2009a; 2010). These excavations have shown that new settlements arose during the 6th century along the river channel of the Oude Rijn, of which the majority persisted during the 7th and 8th centuries. Most were abandoned before the 9th century AD, whereupon the countryside appears to have been nearly deserted during the 9th and 10th centuries, which was the time of Viking raids and evacuation of the bishop seat in ~ AD 850-930 (Van Rooijen, 2010). After the bishop's return in the 10th century, the population increased and Utrecht once again became a centre of religion, politics and trade. This culminated in a large walled 12th-century Medieval city (De Bruijn, 1994). The episcopal property of the Church of Utrecht was split up during the 10th and 11th centuries (Specht, 1695 and 1696; De Bruijn, 1994). During this period the number of convents, monasteries and secular settlements on the alluvial ridges in the area increased rapidly. The city also hosted a residence (*Pfalz)* for the emperor of the Holy Roman Empire. The flood basins and peat areas next to the alluvial ridges were colonized from the 11th century onwards after the bishop of Utrecht had granted concessions to groups of colonists (Dekker, 1983; Henderikx, 1987; Buitelaar, 1993).

The damming of the Rhine near Wijk bij Duurstede in AD 1122 would have resulted in the loss of riverine trading routes to Utrecht. Therefore, bishop Godebald (AD 1114-1127) not only granted city rights to the civilians of Utrecht in AD 1122, but also permitted the construction of canals. The Medieval city was allowed to erect a defence wall and trench (*OSU* I nr. 308; De Bruijn, 1994). Two natural segments of the Medieval Rhine, respectively located ~700 m north and 1 km south of the former fort, were used to delimit the city in the north and south, thereby forming slightly curving boundaries (Apps. F, G). Two straight canals were dug between these channels to form the east and west boundaries enclosing an area of ~125 ha (Van Vliet, 2000a). In addition, a canal was dug within the city between AD 1122-1127: the Oudegracht or *novum fossatum* (*OSU* I nr. 322). Finally a ~8 km long canal, named Vaartse Rijn, was dug in order to restore a connection with the Hollandsche IJssel (and Lek) river to the south (Figs. 6.8 and in Appendix D: Figs. D4, D6 and D8).

In summary, the alluvial ridges of the Kromme Rijn and Oude Rijn were semi-permanently inhabited throughout the studied time interval. During the 2nd millennium AD, land in the wider surroundings was reclaimed and Utrecht became a permanent city on an abandoned alluvial ridge.

6.3 Combining geological and archaeological data

The study of the abandonment phases of the Kromme Rijn and Oude Rijn requires a detailed reconstruction of the palaeogeographical development. To this end we first produced a geological-geomorphological map of the area, mainly in order to delimit the channel belts and to reveal existing residual channels within these belts (section 6.3.1). To provide tight age control these channel belts and residual channels were dated using various geological and archaeological dating techniques (section 6.3.2; Tables 6.3-6.5; extensive detail is provided in the Appendix D, which contains entries at channel belt and site level). Occasionally, the direction of channel migration has been exposed in sections during archaeological research. Subsequently, the position and migration of the former river channels through time were reconstructed, thereby revealing the chronological development of the meander lengths and amplitudes (section 6.3.3). Finally, the original channel bathymetry and the palaeo-discharge of the channels during the abandonment phase were reconstructed (section 6.3.3). The reconstruction of the interaction between landscape development (river activity) and human occupation during the abandonment phase was based on the reconstruction of settlement history of the area (section 6.3.4).

Overall, a large amount of legacy data and earlier compiled maps were analysed and supplemented with data from more recent studies carried out during the last two decades up to mid-2014. Here we only refer to overview publications and peer-reviewed archaeological literature.

6.3.1 Geological-geomorphological mapping

To reconstruct the palaeogeographical development of the study area during the Roman and Medieval periods we mapped and dated the morphological features in both the rural and urbanized parts (Fig. 6.4). This reconstruction ties in with existing reconstructions at delta scale and with full Holocene coverage (Berendsen and Stouthamer, 2000) and with associated mapping-and-dating GIS databases (Cohen *et al.,* 2012b). Particular attention was paid to the position of the residual channels and to their respective ages.

The palaeogeographical reconstructions in the rural areas are mainly based on soil, geological, lithogenetic and geomorphological maps (Berendsen, 1982; Buringh and Van der Knaap, 1952; Stichting voor Bodemkartering, 1976; Van der Meene, 1988). These maps have regional coverage and reveal the detailed distribution of the meander belts, levees, crevasse splays and flood basins, with the exception of the urbanized areas. The mappings are based on an extensive database of Utrecht University containing over 150-300 shallow (2-5 m depth) borehole descriptions per km^2 (Berendsen, 1982; Berendsen and Stouthamer, 2001; Berendsen *et al.,* 2007). These corings were performed with hand auger equipment and described in a uniform way. The boundaries of the mapped features were improved by analysis of LIDAR data of national coverage (Appendix D – Section B: Figs. D.5a, D.5b; Rijkswaterstaat-AGI, 2005; Berendsen and Volleberg 2007; De Boer et al. 2008; Chapter 2).

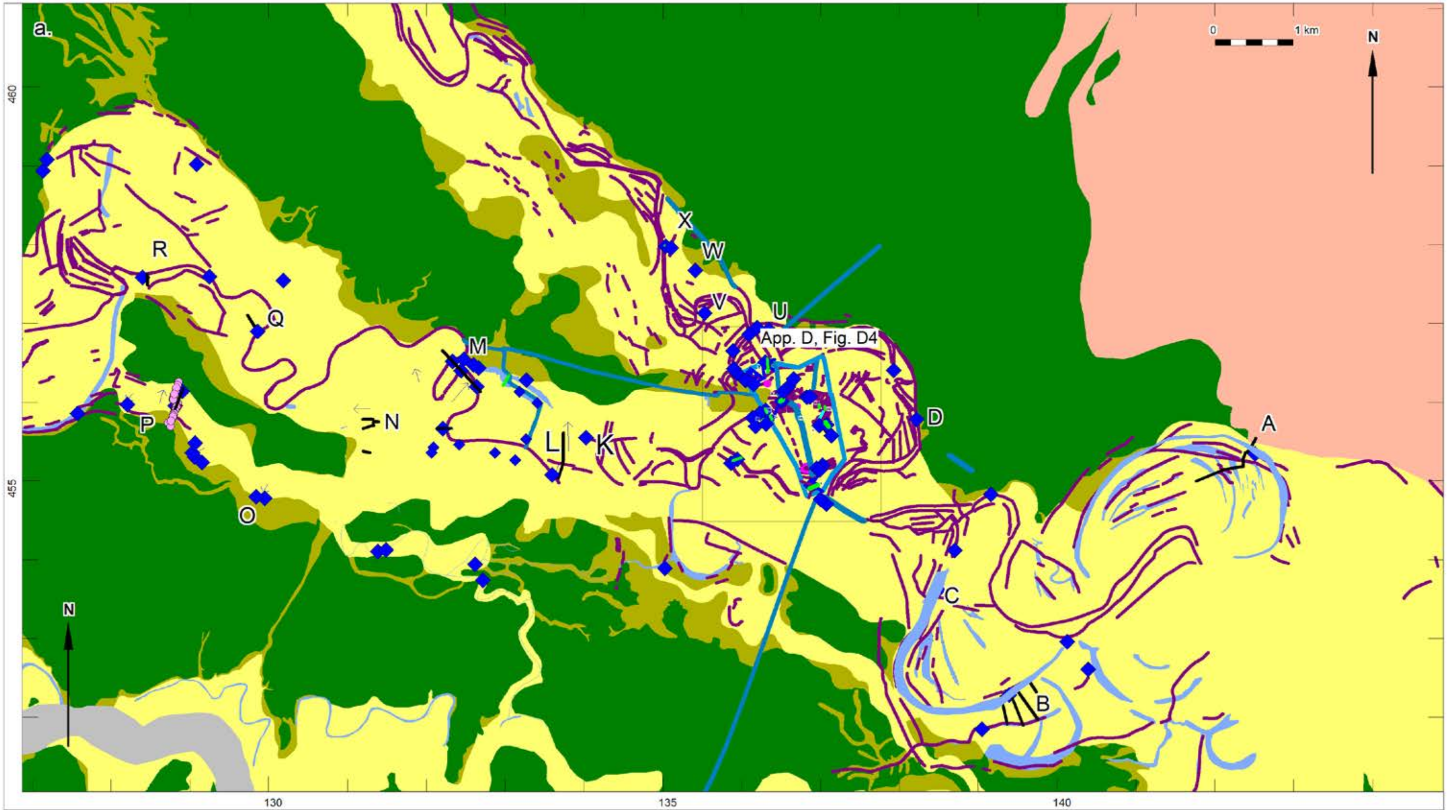
For the reconstructions in the urbanized areas, we studied and re-evaluated maps resulting from earlier analyses of the core descriptions database of the municipality of Utrecht (Wansleeben, 1982; Nales and Vis, 2003). In addition, historic topographical maps were studied to locate curved ditches and roads, and to assess in which cases these are indicative for the presence of residual channels (Fig. 6.4a; Van Deventer, 1569/70; Blaeu, 1633-1635, 1649; Verstraelen, 1629; Specht, 1696; Anonymous, 1873, 1874, 1875).

Descriptive geological information from archaeological excavations in the area was used to verify the mapped boundaries of the geomorphological units. In addition, this resource was important for documenting the dimensions (width, depth) of (residual) channels and the directions of channel migration in time and space *within* the channel belt (Fig. 6.4b). A major part of the palaeogeographical reconstruction work was comprised of deriving this information from the source data and recompiling it into maps and figures (Figs. 6.4-6.6).

6.3.2 Age control

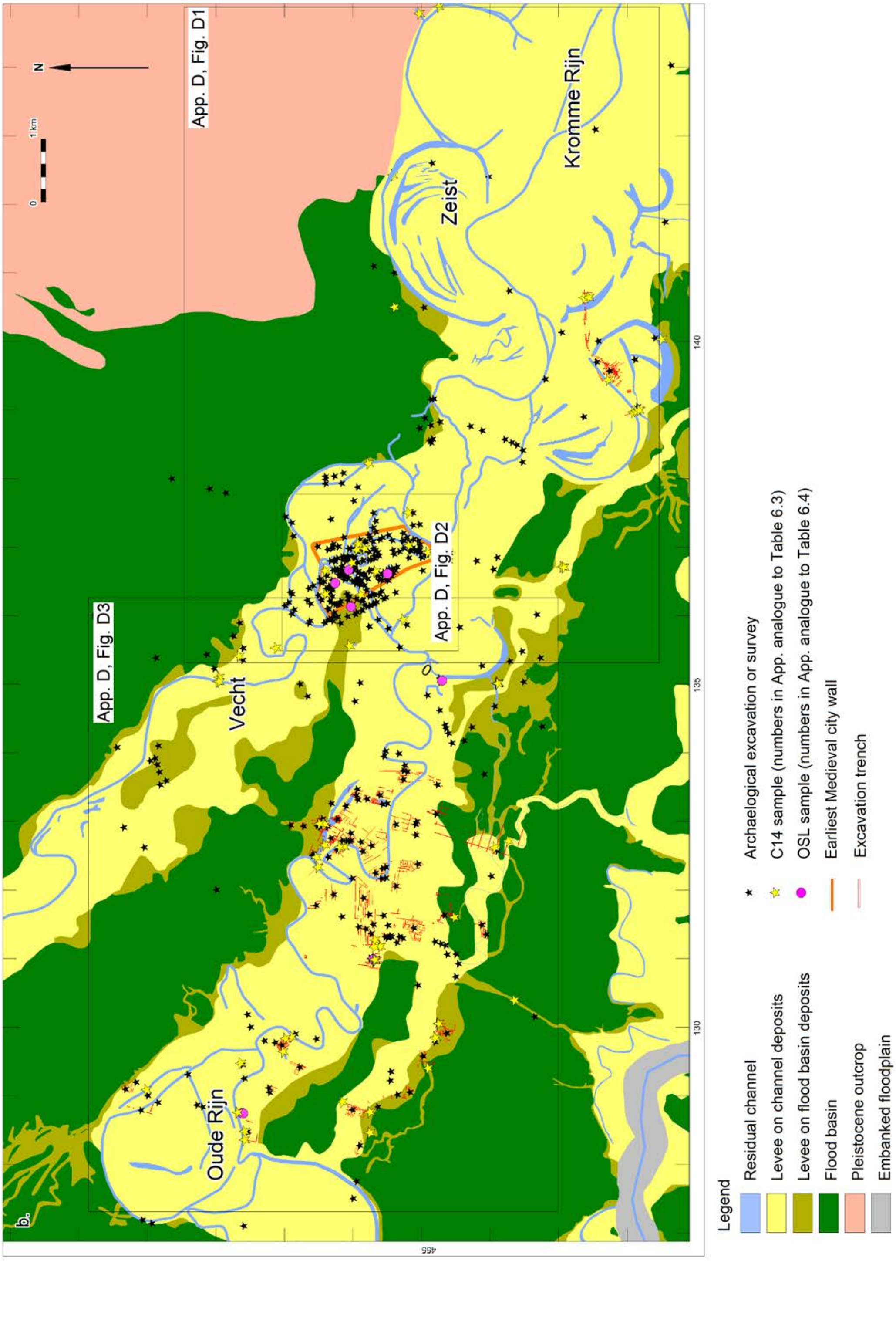
The results from the many archaeological excavations in the area were used to provide tight age control of the mapped geomorphological elements. Archaeological artefacts such as pottery and metal finds usually can be dated quite accurately, particularly when produced during the Roman and Medieval periods. Dealing with an assemblage of artefacts usually reduces the dating range of the finds to a few decades with a maximum of one century. Likewise, the time frame during which the various channels were abandoned and filled in is constrained by archaeological dates from accumulated waste in the residual channel fills. This approach yields more accurate results than radiocarbon and OSL dating of geological material alone. In addition dendrochronological dates of sunken vessels which sometimes contain preserved archaeological remains yielded estimates of the period of channel activity (e.g. De Groot and Morel *et al.,* 2007; Jansma and Morel, 2007; Jansma, 2013; Jansma *et al.,* 2014b; Manders, 2011; Manders and Hoegen, 2011; Brouwers *et al.,* 2013; Brouwers *et al.,* 2015). Finally, at some locations excavated bank revetments showed the presence of (residual) channels (Van Rooijen, 2010; Ypma *et al.,* 2014). These revetments consist of a series

Figure 6.4 (next pages) Geomorphological map of the study area, a. with location of cross-sections (Fig. 6.5c), used for the reconstruction of river channels (capitalised labels corresponding to Table 6.5), directly observed residual channels, and indirect observations of these channels as curved ditches, roads and waterways. Detailed maps for the medieval city subarea are found in Appendix D (Section A, Fig. D4); b. with locations of archaeological excavations and surveys (centre coordinates), ^{14}C and OSL sample sites. More detailed maps are part of Appendix D (Section A, Figs. D1-3).



Legend

- Cross-section used for reconstruction of river channels (letters analogue to Figure 6.5c and Table 6.5)
- Old ditches, roads and waterways
- Direction of river movement
- Observed residual channel
- Coring (Nales & Vis, 2003)
- Medieval canal


b.
N
0
1 km
App. D, Fig. D1
App. D, Fig. D2
App. D, Fig. D3
Zeist
Kromme Rijn
Vecht
Oude Rijn
130
135
140
455
Legend
Residual channel
Levee on channel deposits
Levee on flood basin deposits
Flood basin
Pleistocene outcrop
Embanked floodplain
Archaelogical excavation or survey
C14 sample (numbers in App. analogue to Table 6.3)
OSL sample (numbers in App. analogue to Table 6.4)
Earliest Medieval city wall
Excavation trench

of vertical wooden poles, usually holding a board or wicker work in order to stabilize the river bank and to support mooring. The revetments were not intended to defend against erosion.

Archaeological finds uncovered in natural levee deposits are usually not reworked and therefore were considered to reveal the period of river-bank formation. In contrast, artefacts excavated in channel deposits are either considered to have been re-deposited from the vicinity, and thus to pre-date sedimentation, or to have been have been thrown into or lost in the river, thus representing the formation period of the deposits. In addition, the age of archaeological settlements and finds discovered in paleosols (vegetation horizons) formed in the top of levee deposits, which indicates a former surface, provided *terminus ante-quem* dates of the levee formation.

The spatial extent of a (buried) weak soil horizon was used to map the pre-Medieval channel belt parts. Artefacts in this palaeosol show that it was formed during the Roman period in the top of the adjacent and older channel belts in the area. This palaeosol is easily recognizable by its dark grey to black colour and is characterised by the absence of calcium carbonate, which indicates a period of soil formation and limited sedimentation.

The first step was to analyse the archaeological excavations that have been carried out by the Utrecht Archaeological Service in the Medieval city of Utrecht and its direct surroundings since the early 1900s (Fig. 6.4b; Appendix D: records 1-204 of Table D1). Relevant geological information of these sites was obtained from the short descriptions of the excavation results, which mainly have been published in the annals of the municipality of Utrecht. In addition, geological information was acquired from the archaeological reports of excavations that were carried out in the urban areas and the rural surroundings by archaeological companies (Fig. 6.4b; Appendix D: records 205-412 of Table D1).

During the last decades the Utrecht Archaeological Service also conducted a number of large-scale archaeological studies to the west of the city of Utrecht in the new residential area around De Meern, 'Leidsche Rijn', which now covers ~ 25 km^2 (Figs. 6.2, 6.4b; Appendix D 6: records 413-502 of Table D1). Geological research constituted a major aspect of these studies and at each excavation the cross-sectional architecture was logged for lithology and sedimentology, and the facies distributions were interpreted lithogenetically. Age control was obtained in these studies by radiocarbon and optical stimulated luminescence (OSL) dating, and by the chrono-typological study of the archaeological finds.

To estimate the period of abandonment of the various river channels a combination of dating techniques was used, thereby chronologically constraining the abandonment phases within narrow boundaries (Tables 6.3-6.5 (presented at end of this Chapter); sandy strata: OSL-dating and ^{14}C-dating of enclosed organic mats, dendrochronological dating of boats; residual channel fill: ^{14}C and archaeological dating of muddy, organic and/or antropogenic waste). The results of individually dated residual channel fragments throughout the Roman and Medieval periods were integrated into a palaeogeographical reconstruction following the abandonment of the Kromme Rijn-Oude Rijn and the Vecht channel belts. This reconstruction complements and improves the existing chronology of the avulsion history of the central Rhine-Meuse delta (Berendsen, 1982; Stouthamer and Berendsen, 2000; Berendsen and Stouthamer, 2001; Cohen et al. 2012), which focused on the earlier parts of the Middle and Late Holocene (up to Roman times), mostly relied on ^{14}C-dating, and intrinsically assumed a relatively fast pacing of avulsion and abandonment.

6.3.3 Reconstruction of channel geometry and palaeo-discharge

The various sources revealed the ages and locations of residual channels (Fig. 6.4) and provided information about the dimensions of the former active river channels (Table 6.5) and/or the direction of channel migration. This resulted in the reconstruction of the position of the former river channels in the research area through time as well as the meander length and amplitude of the successive river channels. The palaeogeographical reconstructions distinguish a sequence of stages of which the chronological boundaries are primarily based on morphological changes, and which also show the corresponding changes within the archaeological record.

Figure 6.5 (next page) shows the principles deployed in reconstructions of former channel dimensions from lithological cross-sections (Fig. 6.5a, b), as well as selected key examples of actual studied cross-sections (Fig. 6.5c, ordered by location and age; also see Table 6.5). The depths of former channels (Table 6.5) were estimated from the thickness of channel-bed deposits (corings reaching to thalweg channel-lag deposits) and the depth of the base of residual channel fills, where these are metres thick and the transition signals sudden abandonment and subsequent quick transformation into an oxbow lake (cf. Constantine *et al.,* 2010; Toonen *et al.,* 2012), such as in the Oudwulvenbroek example (Fig. 6.5c: section B; based on Jansen *et al.,* 2014 and Van den Bos *et al.,* 2014). The width of former channels (Table 6.5) was estimated from the planform geometry of oxbow lake residual topography (trench exposure + borehole-based mapping, LIDAR data), presence of relatively fine-grained fill deposits (sedimentary architecture), the presence of revetments and trodden river banks (archaeological indicators), and the distance between curved older roads and ditches (inferred topographic inheritance).

Next, the relative channel erosive capacity was reconstructed based on the observed changes in channel morphology and activity. An absolute palaeo-discharge at bank full discharge estimate was not reconstructed because flow velocities cannot be directly compared to modern ones because of major engineering works. However, 18^{th}-century flow velocity measurements in the Rhine branches in the upper delta, performed before major engineering works such as cut offs and groynes took place (Table 6.2; Hesselink *et al.,* 2006), probably yield a reasonable indication for the beginning abandonment stage of the Oude Rijn at the start of the Roman Period with estimated flow velocities of ~1 m/s in the centre of the channel and 0.5 m/s in riparian areas.

6.3.4 Reconstruction of settlement history

The reconstruction of the settlement history is based on the results of all archaeological excavations and surveys in this area. The occupation of archaeological sites on the Utrecht alluvial ridge is usually dated with a confidence range of ~ 25-50 years.

The outline of the Roman forts in the area is known from a number of excavations and surveys in and around the forts (Vechten: Polak and Wynia, 1991; Zandstra and Polak, 2012; Utrecht: Ozinga *et al.,* 1989; De Meern: Vollgraff and Van Hoorn, 1941; Jongkees and Isings, 1963; Kalee, 1982; Kalee and Isings, 1980, 1984; Van der Gaauw and Van Londen, 1992). Likewise, the contours of the civil Roman settlements that developed in time around these forts, generally called *vici*, have been reconstructed in previous studies in various detail (Vechten: Vos, 1997; De Haan, 2004;

Table 6.2 Flow Velocities and Discharge of the river Rhine near the Dutch-German border in 1790 and 1792 (after Hesselink *et al.,* 2006: cross section river Boven Rijn – a,A). * = bankfull discharge.

	v (m/s)			Q (m^3/s)
	Min.	**Max.**	**Average**	
AD 1790	0.85	1.45	1.1 ± 0.13	1,745
AD 1792*	0.65	1.85	1.3 ± 0.22	3,370

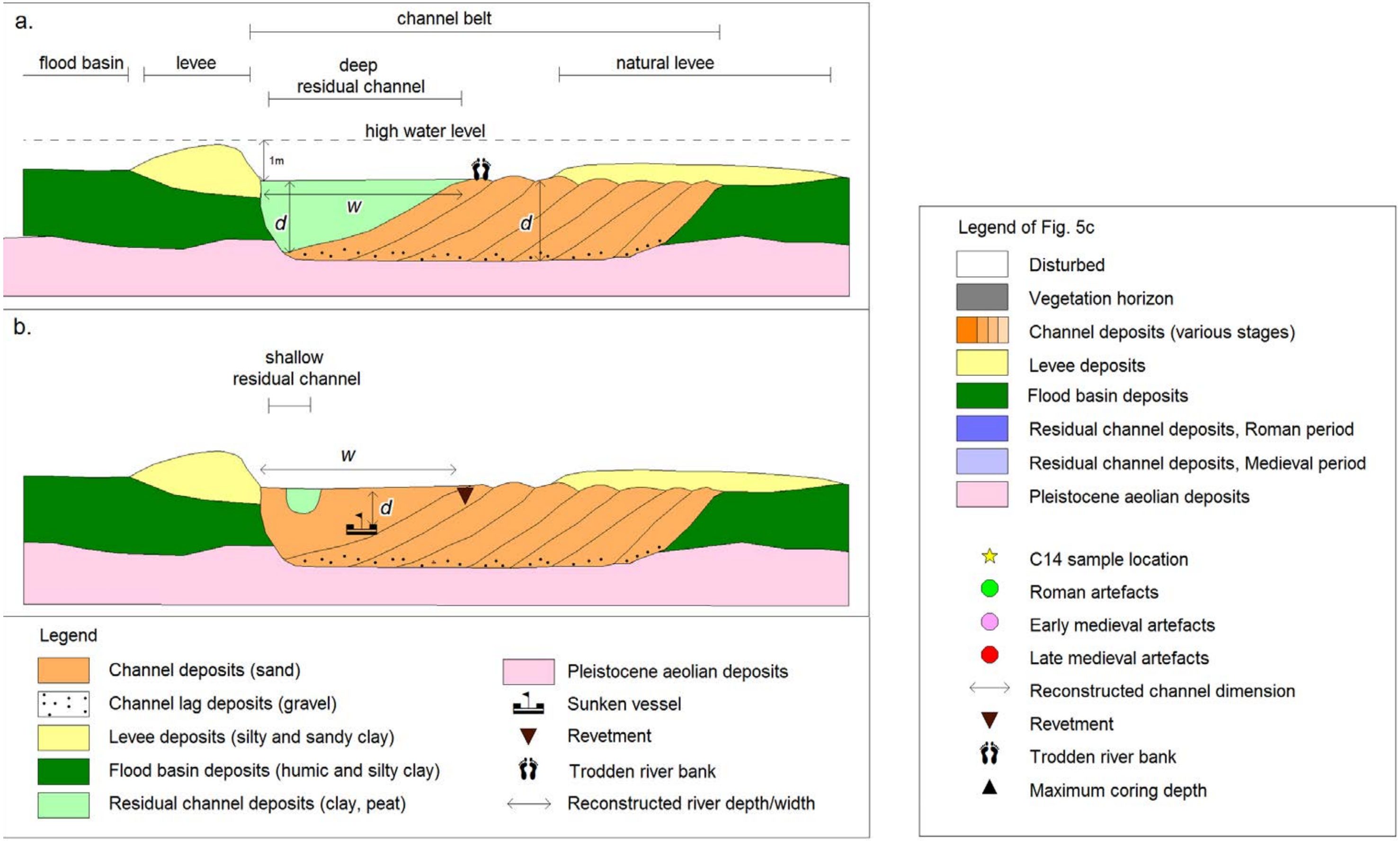


Figure 6.5 a. and b. Schematic cross-section showing method of reconstruction of channel dimensions; c. Selection of cross-sections (capitalised labels corresponding to Table 6.5), ordered east to west and from Roman to Medieval period, showing dimensions of the river channels in time and space. For locations of sections, see Fig. 6.4 and the local data Appendix D (Section B, Fig. D5).

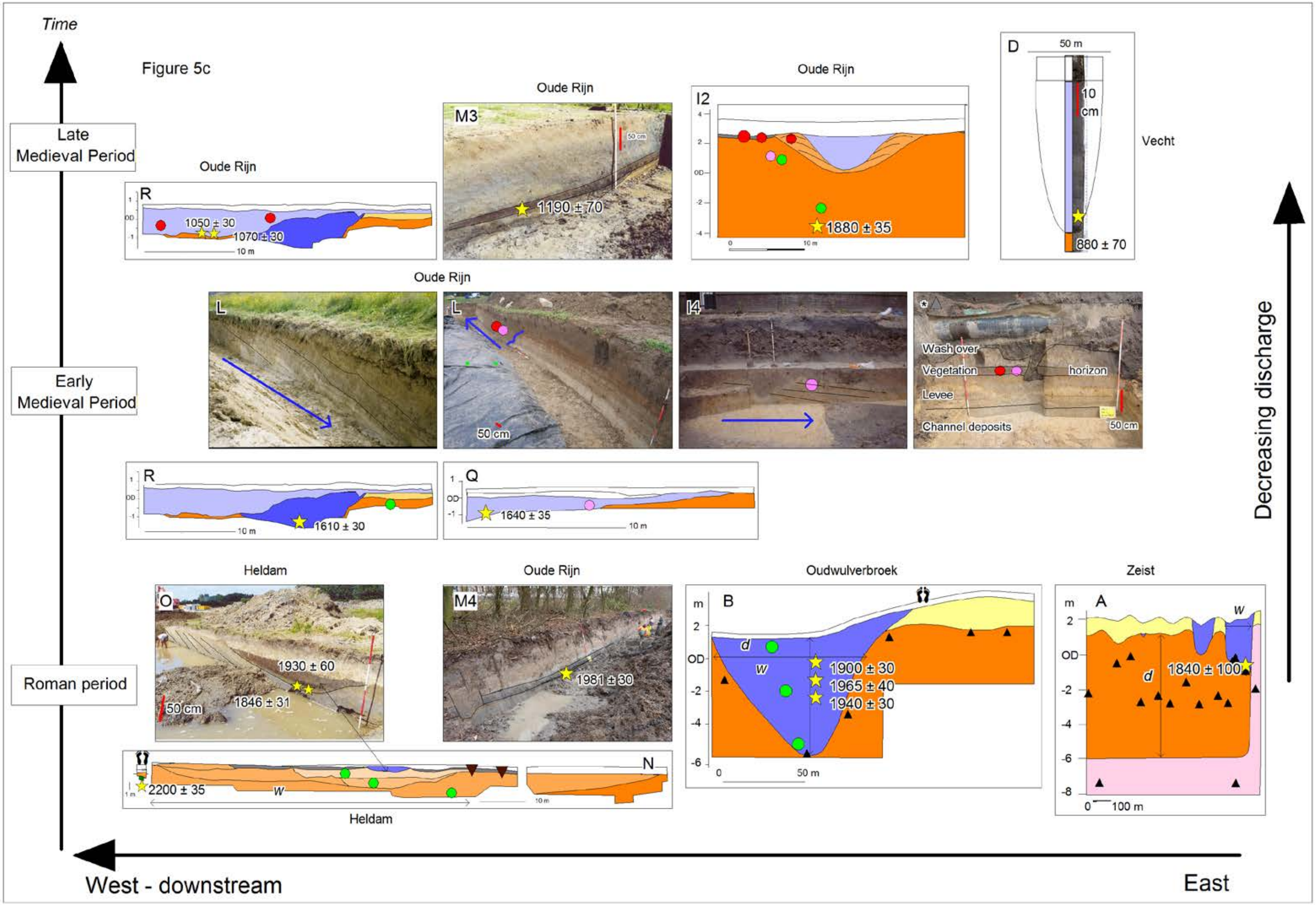


Figure 5c
Time
Late Medieval Period
Early Medieval Period
Roman period
West - downstream
East
Decreasing discharge
Oude Rijn
R
1050 ± 30
1070 ± 30
10 m
M3
1190 ± 70
50 cm
I2
1880 ± 35
10 m
D
50 m
10 cm
880 ± 70
Vecht
L
50 cm
I4
Wash over
Vegetation
horizon
Levee
Channel deposits
50 cm
R
1610 ± 30
10 m
Q
1640 ± 35
10 m
Heldam
O
1930 ± 60
1846 ± 31
50 cm
M4
1981 ± 30
Oudwulverbroek
B
d
w
1900 ± 30
1965 ± 40
1940 ± 30
50 m
Zeist
A
w
d
1840 ± 100
100 m
2200 ± 35
w
N
10 m
Heldam

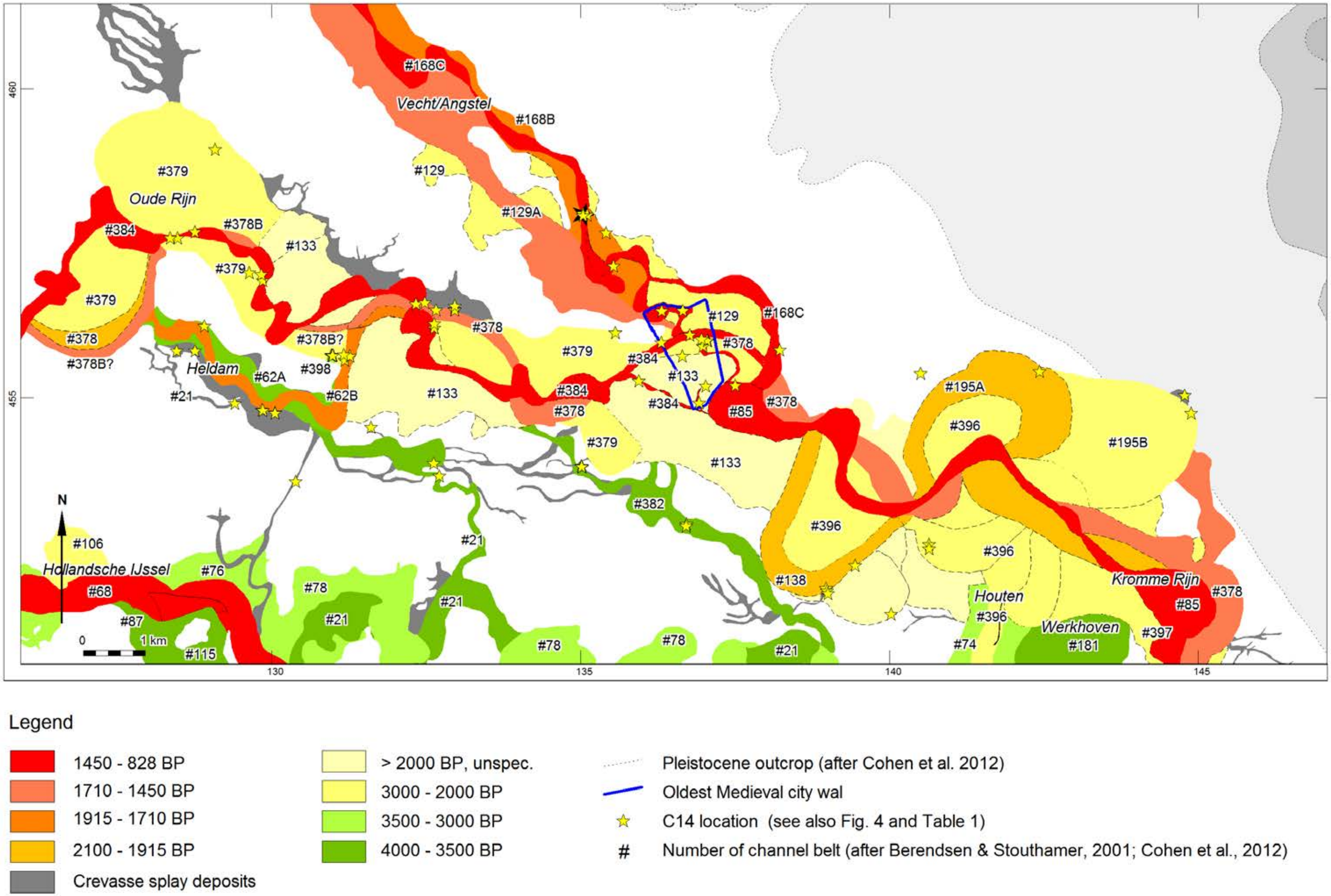


Figure 6.6 Updated map of the channel belt age for the study area (Channel belt #ID's serve as cross-reference to Fig. 6.7, descriptions in Appendix D – Section B, and earlier mapping cited therein). Stars show locations of 14C dating control (Table 6.3).

Utrecht: Ozinga *et al.,* 1989; Montforts, 1991, 1995; De Meern: Haarhuis and Graafstal, 1993; Van der Gaauw and Van Londen, 1992; De Jager, 2000; Langeveld *et al.,* 2010; Langeveld, in press). The location of the Roman watchtowers in between the forts was derived from Van Dinter (2013), and the distribution of the rural settlements in the Roman period was obtained from Haarhuis and Graafstal (1993), Kooistra et al. (2013) and Van Dinter (2013). The presence of several Roman cemeteries in the vicinity of the forts was demonstrated by Polak (1997), De Haan (2004), Langeveld et al. (2010), and Duurland (in press). The reconstruction of the Roman road was based on Luksen-IJtsma (2010), and has been slightly adapted based on recent excavations.

The distribution of the Early Medieval settlements between AD 500 and 800 was derived from Nokkert et al. (2009), complemented with data from Den Hartog (2010) and Van Rooijen (2010). A property list drawn up by bishop Radbod in AD 914 to reclaim the church possessions before his return to Utrecht, the *commemoratio de rebus Sancti Martini Traiectensis ecclesie* (Henderikx, 1987; De Bruijn, 2008), was consulted in order to hypothetically link its content to archaeological finds. The locations of Medieval settlements between AD 800 and 1200 were based on Haarhuis and Graafstal (1993), Van Rooijen (2010), Van der Kamp (2005a, 2005b, 2006a, 2011, 2013), Den Hartog (2009b, 2013c), and Dielemans (2010). The location of Late Medieval churches and the extent of their ecclesiastical properties were obtained from Hoekstra (1989) and De Bruijn (1994).

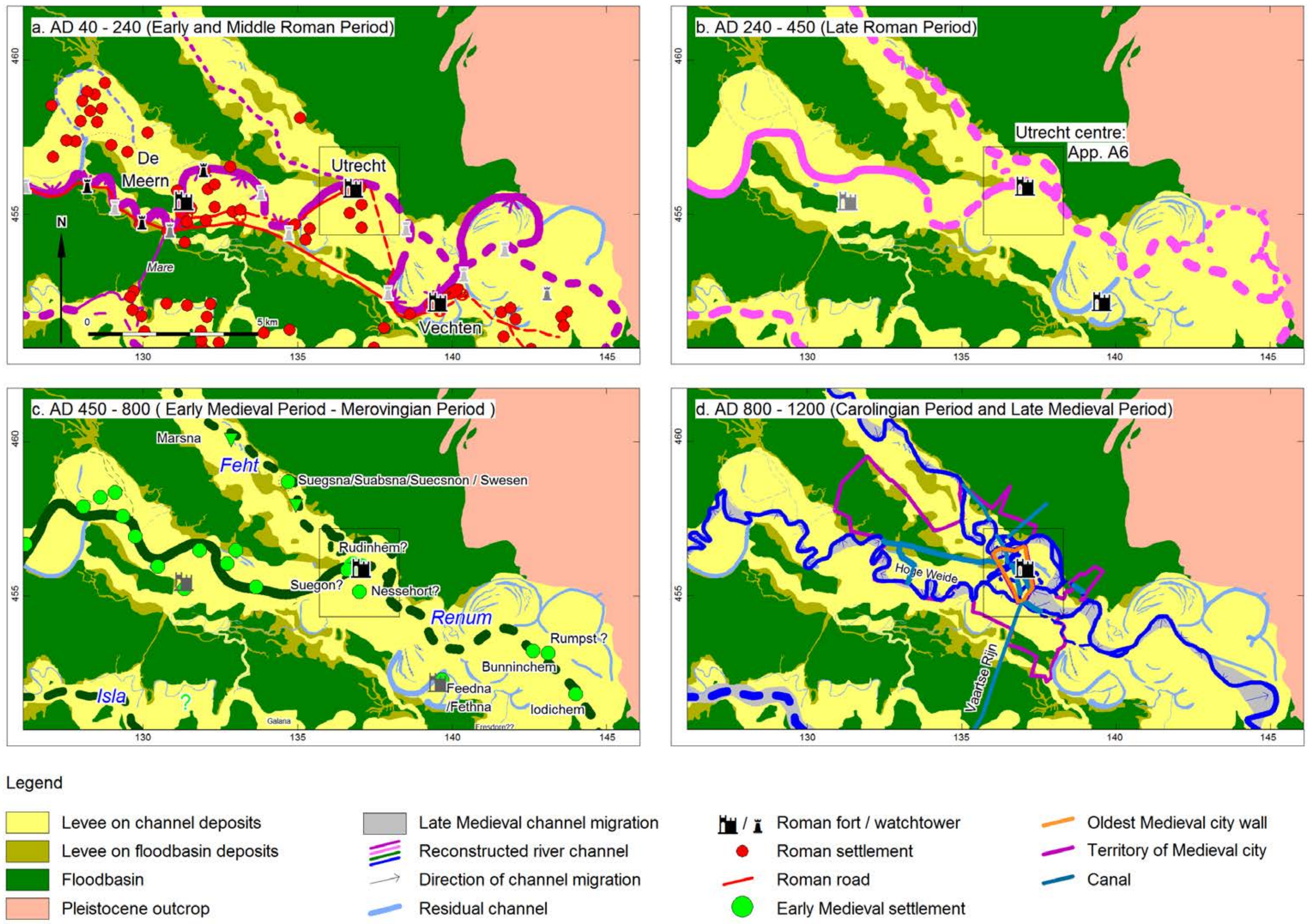
6.4 Palaeogeographical development and habitation history

This section describes the palaeogeographical reconstruction of (i) the landscape development and (ii) settlement pattern. River dynamics are discussed in downstream direction (from east to west) and in chronological order. To create an overview a channel belt age map was compiled (Fig. 6.6). This map integrates the various sources described above, thereby updating previous reconstructions (Berendsen and Stouthamer, 2001; Cohen *et al.,* 2012b), and shows the width and age of the various channel belt segments associated with activity of the youngest channel belt (red colors) within the long-lived channel belt (yellowish colours). Figure 6.7 provides an overview of the period of activity of the main distributaries on a time axis. Channel belt segment numbering (#IDs) follows Berendsen and Stouthamer (2001) and Cohen et al. (2012).

6.4.1 Early and Middle Roman period (AD 40-240)

River and landscape

During the first two centuries AD (Fig. 6.8a), relatively large and wide meanders characterized the Rhine channel upstream of Utrecht. Examples are the so-called Zeist (#195) and Oudwulvenbroek (#138) with a meander length of ~ 4.5 km and an amplitude of ~ 1-1.5 km. The sinuosity index was ~1.5. The Roman fort in Vechten was situated on the outer bank of the latter meander. The channel in front of it was ~100 metres wide and 7 metres deep. This channel, however, hardly migrated and the large meander bends should be considered as a relic from earlier Iron Age stages when the river discharge had been larger because the competing avulsive distributaries of the Krimpen system (Figs. 6.2, 6.3) had not yet established. The meanders were most likely cut off simultaneously in the second half of 1st century AD and rapidly silted up during the Roman occupation. In the same period a darkened palaeosol developed on the alluvial ridges regionally; this horizon is characterised by an A-horizon with black colour, devoid of calcium carbonates, overlying an immature illuviated B-horizon (Berendsen 1982; Schoute, 1984; Steenbeek, 1990). The paleosol is preserved below


a. AD 40 - 240 (Early and Middle Roman Period)
De
Meern
Utrecht
Vechten
Mare
N
0
5 km
b. AD 240 - 450 (Late Roman Period)
Utrecht centre:
App. A6
c. AD 450 - 800 (Early Medieval Period - Merovingian Period)
Marsna
Feht
Suegsna/Suabsna/Suecsnon / Swesen
Rudinhem?
Suegon?
Nessehort?
Renum
Rumpst ?
Bunninchem
Feedna
/Fethna
Iodichem
Isla
?
Galana
d. AD 800 - 1200 (Carolingian Period and Late Medieval Period)
Hoge Weide
Vaartse Rijn
460
455
130
135
140
145
Legend
Levee on channel deposits
Levee on floodbasin deposits
Floodbasin
Pleistocene outcrop
Late Medieval channel migration
Reconstructed river channel
Direction of channel migration
Residual channel
Roman fort / watchtower
Roman settlement
Roman road
Early Medieval settlement
Oldest Medieval city wall
Territory of Medieval city
Canal

overbank deposits from later stages of the abandonment phase. This paleosol indicates that the first centuries AD were characterized by a prolonged period of low overbank sedimentation, i.e. limited river activity outside the active channel, whereas its preservation indicates increased overbank sedimentation later on. It is interesting to note that all Early and Middle Roman rural settlements are positioned on this soil horizon.

With the cut-offs during the Roman Period, the river developed a straighter course. The cut-off channel shows a weakly meandering channel with some in-channel bars within a ~300 m wide zone (Appendix D – section B: Fig. 5b). This indicates that the new channel was in disequilibrium with the river discharge, demonstrating that the river discharge further diminished during the Middle Roman Period. This is in agreement with the avulsion history of the wider delta, with the Lek and Waal distributaries gaining importance at this time (Fig. 6.3). The sand-choked channel bed morphology in the channel fill of the Zeist (#195) meanders (upstream of Utrecht) probably originates from the 2nd to (early) 3rd centuries AD.

The bifurcation of the Rhine into Oude Rijn and Vecht was situated ~ 7 km downstream of the fort near Vechten, right in front of the Utrecht fort. Just upstream of the bifurcation, the river channel was ~5-6 m deep and ~100-120 m wide. During the Roman occupation phase the river migrated several tens of meters northward, facilitating an enlargement of the Roman fort in a northern direction at the start of the 3rd century AD. Just downstream of the bifurcation, the Oude Rijn river channel was ~160 m wide and most likely only ~3-3.5 m deep. Similar to the cut-off reach described upstream, a sand-bar choked river bed developed here. The morphology and width of the river Vecht at this time is unclear since no evidently Roman age segment of this river has been identified so far. Presumably, the distribution of discharge over the bifurcation began to tip

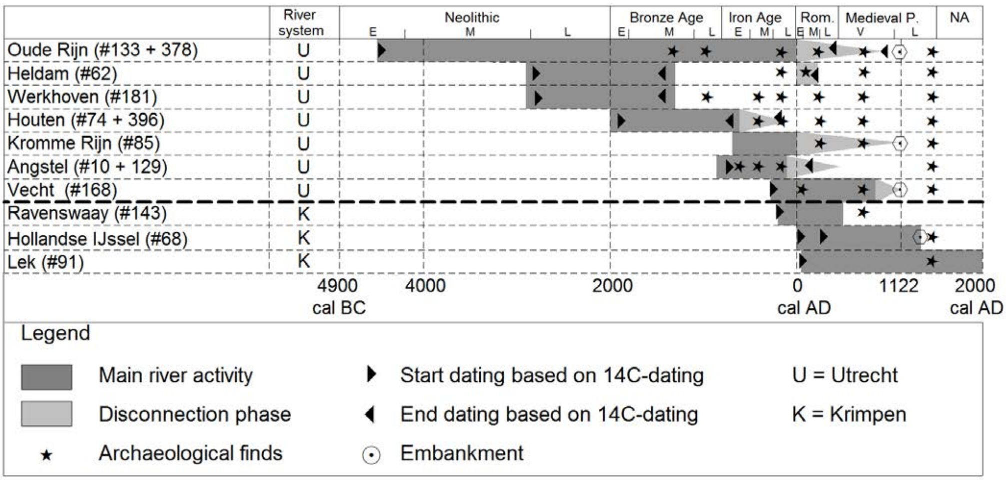


Figure 6.7 Period of activity of the main channel belts (Fig.6. 6) affecting the study area in the Late Holocene.

Figure 6.8 (left) Palaeogeographical maps of the study area with river channels and settlements: a. AD 40-240 (Early and Middle Roman Period), b. AD 240-450 (Late Roman Period), c. AD 500-800 (Early Medieval Period – Merovingian Period) and d. AD 800-1200 (Carolingian Period and early part of Late Medieval Period).

towards the Vecht channel in this particular period, as suggested by a contemporary shallowing of the channel of the Oude Rijn downstream of the Utrecht fort (Fig. 6.5).

In the western part of the research area, the Heldam channel belt (#62B) was the main active channel at this time, whereas the Oude Rijn's main alluvial ridge to the north only seems to have hosted residual channels. The activity of the Heldam channel marks a reoccupation phase of this channel belt, which appears to have started early in the 1st century AD. The river channel was ~90 m wide and ~4 m deep in front of the Roman fort in De Meern, while it was ~6 m deep and only ~60 m wide further downstream (Figs. 6.4 and 6.5: section O). The channel dimensions were only modestly smaller than those of coeval channels upstream of the river Vecht bifurcation. Based on cross-sectional hydraulic considerations (width: 4.5-6 m; depth: 60-90 m), the Heldam channel alone was able to transport all the discharge routed westward over the Oude Rijn-Vecht bifurcation. Hence, the dimensions of the river Vecht in Roman times were estimated from the differences in cross-sectional area, which was about 100 m^2, implying a depth of ~4 m and a width of depth and ~25 m (Fig. 6.9).

The river Heldam (Fig. 6.6) shifted over a distance of maximum 200 m in a downstream direction and laterally over ~50-150 m, thereby forming pronounced meander bends with a length of ~1 km and an amplitude of ~300 m. By the end of the 2nd century/early 3rd century the Heldam river channel started to silt up and in the second quarter of the 3rd century this river branch was completely abandoned, leaving a small residual channel of ~10 m wide and 1 m deep. Channel migration continued during the abandonment phase and at some locations the shallow river channel even migrated slightly out of its sandy channel belt.

At ~1 km south of the fort in De Meern a southwesterly orientated crevasse channel, the Mare, was active. Its channel was ~3.5 m deep and 15 m wide. Presumably a relatively short canal was dug to link this channel to a crevasse channel from the IJsselveld – Schuurenburg (#76) channel. In this manner, the Mare canal connected the Rhine to the young Hollandsche IJssel (#68) channel of that time.

Settlement pattern

Three strategically situated Roman forts were built in the research area during the 1st century AD on similar locations as those of the *Limes* forts further downstream along the Oude Rijn (Chapter 2). The Oudwulvenbroek meander, along which the Roman fort in Vechten was situated, was probably cut off in the second half of 1st century AD and rapidly silted up during the Roman occupation phase, mainly because the residual channel functioned as a dump area (Van den Bos *et al.,* 2014).

Watchtowers were built between the *castella* during the second part of the 1st century AD to complete the river view (Chapter 2). Several tower sites have been discovered so far. One of these, on the Heldam alluvial ridge, was relocated in response to river-bend migration during Roman occupation (Langeveld and Luksen-IJtsma, 2010; Chapter 2).

In addition, a Roman road, the *via militaris*, was constructed on the levees south of the river Rhine from the end of the 1st century onwards following a straight line if possible and cutting short river bends (Chapter 2). Channel migration during the 2nd century caused (partial) destruction of road parts. Subsequently, bypasses were built to overcome the damage (Chapter 2). The *castella* were linked to the *via militaris* by secondary roads. In the second half of the 2nd century, the road segment just east of fort De Meern was swept away by the river (probably due to bend migration undercutting the road). A new road was built further to the south, partly making use of the alluvial ridge of the small Hoograven channel belt (#382).

Soon after the construction of the military forts, *vici* were established close by (Chapter 4). A small *vicus* east of Vechten seems to have been present from the start and the earliest *vici* of De Meern and Utrecht seem to date to the middle of the 1st century. Large-scale development of *vici* only occurred from the end of the 1st century onwards with the creation of the province of *Germania Inferior* by Emperor Domitian in the 80's AD (Chapter 4). These *vici* flourished in the 2nd century and burial grounds were created in the surroundings of all the forts. Moreover, the presence of a Roman bath complex was demonstrated directly north of the fort in De Meern. This upstream location is typical for the bath houses of the chain of Roman forts along the Oude Rijn, most likely because in this manner fresh river water was available instead of water contaminated with sewage water and dirt from the fort.

Native settlements were scattered across the alluvial ridges. These rural settlements mainly relied on an agrarian system based on mixed farming (Kooistra 1996; Groot, 2008; Groot and Kooistra, 2009; Groot *et al.,* 2009). Not all settlements were inhabited simultaneously and some settlements were already inhabited before the large-scale arrival of the Roman army in the area from the '40s AD onwards. Recent research has shown that the number of settlements in the central river delta region increased during the first two centuries AD (Willems, 1986; Groot *et al.,* 2009; Vos, 2009). Changes of the settlement structures indicate that the settlements quickly adapted their economy and were able to produce substantial surplus, supplying the Roman soldiers and the *vicani* with food and other commodities (Kooistra, 1996; 2012; Groot, 2008; Groot and Kooistra, 2009; Groot *et al.,* 2009; Chapter 4; Chapter 5). Most settlements in the research area date to the late 1st and the 2nd century AD and consisted of one or two simultaneously-inhabited byre houses.

6.4.2 Late Roman period (AD 240-450)

River and landscape

During this period (Fig. 6.8b), no major sedimentation occurred on the alluvial ridges as later Early Medieval settlements and archaeological finds are positioned in the same black palaeosol as the one in which the Early and Middle Roman Period sites have been discovered. The Rhine channel upstream of Utrecht was still confined to the ~300 m sand-choked river bed. During this period the discharge of the Utrecht river system further decreased due to continued development of the Krimpen system (Figs. 6.2, 6.3), which in addition to the Lek (#191), Hollandse IJssel (#168) and Linge (#97) now included the river Waal (#174) as a new developing branch.

Nevertheless, changes also occurred in the river network downstream of Utrecht, most notably in the 3rd century AD. After AD 230-240, the Heldam channel accumulated residual channel fill. This indicates it no longer functioned and implies that water was routed through a new channel formed in the Oude Rijn channel belt to the north (Fig. 6.8b). Possibly, also the connection of Rhine and Vecht changed at this time. A new feeding bifurcation developed ~ 1.5 km upstream of the Roman fort. It is also possible that the shifting of this particular location started later, in the beginning of the 6th century AD (see 4.3).

Settlement pattern

Archaeological evidence from the Late Roman Period in the area, i.e. the late 3rd, 4th and early 5th centuries, is scarce. Large-scale inhabitations of the forts and *vici* along the Oude Rijn seems to have continued into the first quarter of the 3rd century (Kemmers, 2008). The finds of the later period, especially dating after AD 275, are sparse and do not seem to indicate permanent occupancy. Habitation in the Utrecht area continued on a small scale only in and around the Roman forts

(Haarhuis and Graafstal, 1993; Van Lidt de Jeude, 1993; Montforts, 1995; Van den Berg *et al.,* 2012). There is no evidence in this area of rural settlement structures dating to the Late Roman Period.

6.4.3 Early Medieval period – Merovingian period (AD 450-800)

River and landscape

By AD 500 (Fig. 6.8c), the river had cut off several of its bends both upstream and downstream of Utrecht. Furthermore, the new bifurcation location of the rivers Rhine and Vecht had established. The Vecht carried an increasingly larger proportion of the discharge – fed to it from upstream.

At some locations along the Oude Rijn channel, such as in Utrecht, the river bed remained choked with sand. Downstream of the former Roman fort, a complex sandy channel fill architecture developed within the wider zone of the channel activity from Roman times (Fig. 6.9). The fill complex reveals the activity of co-existent shallow (2-3.5 m deep) migrating channels. Recently, a vessel now termed the '*Utrecht 6*' was unearthed in one of these channels. It was dendrochronologically dated to c. AD 680 (Jansma, 2013), and its position indicates that shortly after the last quarter of the 7th century this channel started to silt up (Leijnse and Van Mousch, in press). From then on a channel located more to the north was the only one carrying discharge. The uninterrupted presence of the river bank next to an Early Medieval settlement west of Utrecht shows that here the river hardly moved for over ~300 years (Nokkert *et al.,* 2009).

Settlement pattern

Evidence of occupancy of the former Roman forts in the area and their surroundings dating to the 5th century is scarce (Van Rooijen, 2010; Haarhuis and Graafstal, 1993; De Groot, 1994; Hessing *et al.,*1997). The small number of finds near the forts in Vechten and De Meern, mainly ceramics and metal, suggests that these forts only functioned as minor dwelling sites. The most likely cause is that the river along which they were situated was no longer active. This is in contrast to the fort in Utrecht, where finds also are sparse but here luxurious child burials dating to the second half of the 5th century were uncovered next to the castellum, indicating aristocratic presence (De Groot, 1991; Van Es, 1994; Van Rooijen, 1999; 2010). Also, a revetment unearthed ~200 m west of the fort in Utrecht and dated to the 5th or 6th century AD bears witness of human activity at this time.

From the 7th century onwards the fort in Utrecht became a major political and religious centre in northwestern Europe. Various archaeological remains, dating to the Merovingian (AD 447-750) and Carolingian (AD 751-987) periods (Table 6.1), show that human occupancy of the fort in Utrecht continued in this period (Van Rooijen, 2010). A settlement was erected west of the fort, a ditch system was dug south of it, and a Christian burial site dating to the 6th/7th centuries AD was established to the north. The shallow river in front of the fort might explain the Medieval name of Utrecht, *Traiectum* (e.g. *Vita Willibrodi archiepiscopi Traiectensis auctore Alcuino*, p. 120, cap. 5; *Diplomata Belgica* nr. 173, 175, 177, 178, 181 182; *Oorkondenboek van het Sticht Utrecht* (*OSU)* I nr. 35, 43, 45, 48, 62, 63; *Briefe des Bonifatius*: nr. 109), which is generally associated with a ford or crossing (Van Winter, 1975;

Rural settlements started to develop on the levees in the surrounding area from the first quarter of the 6th century onwards. These settlements were all situated on the highest ridges along a river or a re-activated residual channel, and consisted of several farm-houses (Nokkert *et al.,* 2009; Den Hartog 2010; Van der Kamp, in press) The settlements west of Utrecht decreased in size during the 8th century and were abandoned around the start of the 9th century. Data from the eastern part of the research area and the Vecht area are hardly present.

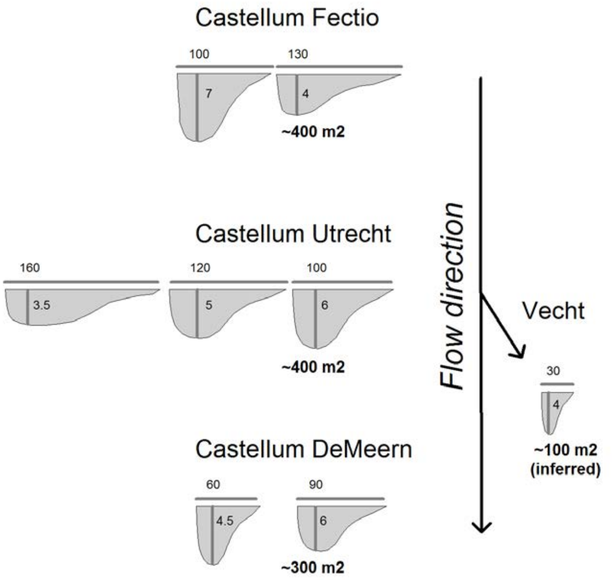


Figure 6.9 Dimensions of the Rhine river channels in the 1st century AD (the time of founding of the Roman forts). Cross-sectional wet area (in m²,calculated for a water level ~1 m below top of levees) is shown for three positions downstream the main river, and for the Vecht distributary. Note vertical exaggeration: graphically the areas do not add up, numerically they do.

6.4.4 Carolingian period and early Late Medieval period (AD 800-1200)

River and landscape

The river Oude Rijn entered its final stage of discharge loss, shrinking channel bed and abandonment (Fig. 6.8d), starting with a last revival of channel migration at the start of the 9th century. This migration was the result of the routing of water through a bed that increasingly had become filled with sediment. Lateral migration mainly occurred within the zone with channel fill from the preceding Late-Roman and Merovingian stages, but in places the shallow river channel also eroded further outwards (Fig. 6.4 and 5: section L). The resulting river had very sharp bends, with a meander length of ~0.8 km, an amplitude of ~100-300 m and a sinuosity index of ~3. The channel was at least 4 m deep in the bends, but its width is unknown (Table 6.5: section M.1). In a relatively narrow zone, extending ~100-200 m along the channel (Appendix D – section B: Fig. 5b), high natural levees developed.

The palaeosol that had formed in the top of the Oude Rijn channel belt in the southern part of the Medieval city of Utrecht (#133) became covered with crevasse splay deposits during this period (Van Rooijen and Wynia, 1997). Within this splay complex at least three small channels were present, which departed from the Kromme Rijn meander that formed the south-eastern boundary of the walled city (Fig. 6.6). The onset of this sedimentation period seems to coincide with the phase of river migration at the start of the 9th century. A Carolingian ditch system (8th-9th century) dug south of the fort in a level above the Roman soil soon filled up and subsequently was buried. The silting-up of the crevasse channels coincided with that of the Vecht channels.

By the end of the 10th century the deepest part of the Oude Rijn channel started to collect an exclusively muddy fill, followed by the shallower river parts in the beginning of the 11th century. This indicates that at that time, most water received from the Kromme Rijn was routed via the Vecht and that the Oude Rijn channel through the city of Utrecht and beyond had become a standing-water body trapping flood sediment only. When the river was dammed upstream at Wijk bij Duurstede in AD 1122, some 100-200 years later, the Oude Rijn residual channel segment was just about 10 m wide and 1-2 m deep.

Like the Oude Rijn, in Carolingian to post-Carolingian times the channel of the river Vecht also started to show increased meandering activity. In this branch, however, this activity seems to have started 150-200 years later – in the second half of the 10th century or early in the 11th century AD. It is suggested that the increased meandering activity of the Vecht indicates the period when discharge received from upstream was passed through the Vecht channel only. The style of lateral migration and in-channel deposition is similar to that of the Oude Rijn in the previous centuries, showing that the volumes of carried discharge were comparably low.

The migration of the Vecht channel in the northwestern part of Medieval Utrecht is demonstrated by a series of elongated revetments following the rapid river migration in a northern direction (e.g., De Groot, 1997; Van Rooijen 1999; 2010; Ypma *et al.,* 2014). The earliest revetments date from the beginning of the 11th century. River migration continued into the first half of the 12th century, when the river started to silt up. A sunken river-going carrier, the Utrecht 1, dating to the early 11th century was excavated from the Vecht channel bed sediments in the northern part of the research area (Van de Moortel, 2009; Brouwers et al. 2015). However, a swale and a channel subsequently developed along it and their dating indicate that the Vecht river channel here silted up only in the 14th century (Den Hartog, 2013c). The 14th-century abandonment was the result of the construction of a canal to the east, the Nye Vecht in AD 1338-1339, in order to cut off the meanders of the Vecht (Appendix D: Fig. D5; De Bruin, 2000). However, the most upstream stretch of the Vecht (connecting to the bifurcation) already began to silt up in the 12th century (880 ± 70 ^{14}C BP; GrA 50894). This demonstrates that the river discharge of the Vecht definitely was reduced by the dam construction at Wijk bij Duurstede in AD 1122. It can be concluded that the river damming at Wijk bij Duurstede merely was the final stage of an already on-going natural process of abandonment, as was already postulated by Vink (1954) and Berendsen (1982).

With the damming and embankment, sediment supply to the study area was strongly reduced. For this reason, it took several centuries for the residual channel east of the Medieval city wall to fill up completely. Consequently, after the damming the residual channel of the Kromme Rijn and Vecht continued to function as natural drains for groundwater seepage water from the nearby ice-pushed ridge (Van Loon *et al.,* 2009).

Settlement pattern

Between AD 857 and century AD 925 the bishop and clergy temporary lived in exile (Hoekstra, 1989; De Bruijn, 1994; Van Rooijen, 1999). This is generally attributed to Viking attacks between AD 834 and 876 (De Bruijn 1994; 1995; Broer and De Bruijn, 1997). However, in Utrecht there are no archaeological indications for such attacks, which would have been recorded for example in the occurrence of layers of burned materials. Furthermore no attacks of Utrecht are mentioned in the *Vita Sancti Liudgeri*, written between AD 839-849. Therefore the bishop's exile also has been ascribed to the political situation of that time (Van der Tuuk, 2003). Since in addition archaeological evidence for habitation dating to the late 9th and early 10th century is lacking in the fort's surroundings, this suggests that the area was temporarily uninhabited. An alternative explanation for the bishop's departure from Utrecht in AD 857 is the occurrence of increased river flooding from AD 800 onwards (Van Rooijen, 1999; 2010), which caused unfavourable habitation conditions. These inundations probably also occurred upstream along the Kromme Rijn and thus further attributed to the fall of *Dorestad* (Kosian et al. 2016).

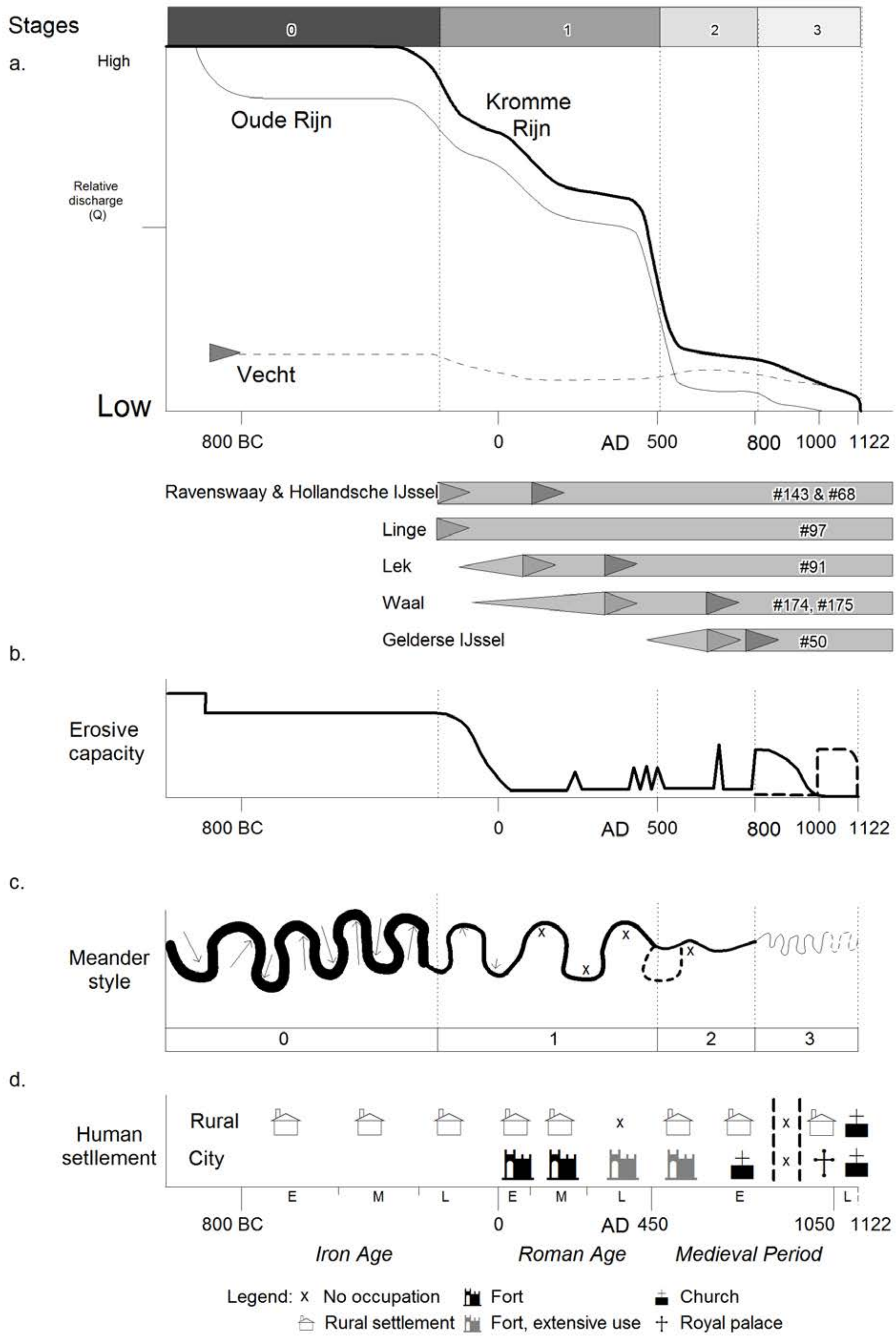


Figure 6.10 Abandonment phases of the Utrecht system with a. relative discharge, b. erosive capacity (peak floodings with recurrence time >100 yr according to Toonen *et al.,* 2013; Cohen *et al.,* 2016), c. development of river pattern and d. human settlement pattern.

The main development of the city of Utrecht took place from the second quarter of the 10th century onwards after the bishop's return to the city. At the end of the 10th century, a settlement was erected along the river, ~500 m north of the fort (Hoekstra, 1989; De Groot, 1997; Van Rooijen,1997; 1999; 2010). This settlement expanded during the 11th century into a large trading centre with quays and bank revetments extending over a length of several hundreds of meters along the river. This settlement only emerged after *Dorestad*'s decline. According to Van Rooijen (2010) this centre was the *Stathe vicus* (*OSU,* nr. 322), a *portus* (harbour) that might have been burnt down during a Viking raid in AD 1007 (*Alpertus van Metz*) or AD 1010 (*Annales Egmundenses*). Previous studies situated this settlement along the river Vecht which was assumed to diverge from the river Rhine south of the fort (Fig. D in Appendix D; e.g. Hoekstra, 1989; De Groot, 1991; De Bruijn, 1994; Van der Tuuk, 1996, 2001; Bruynel, 2001; Van Vliet, 2001a; Renes, 2005; Van Rooijen, 2010). This interpretation implied that no direct connection existed between the settlement and the river channel in front of the former fort. However, the present reconstruction shows that the river bend along which it was situated diverted from the Oude Rijn very close to the fort. The quays and revetments of this settlement indicate that the river channel migrated here over a length of ~300 m in a northern direction and finally started to silt up in the 12th century (Van Rooijen, 2010). By then, the settlement had become nearly abandoned.

Archaeological finds also indicate the nearby presence of other rural settlements in the 11th century, among others ~550 m and ~800 m south of the fort (Van Rooijen, 2010). These in part might be linked to the Medieval settlements mentioned in the *commemoratio de rebus Sancti Martini Traiectensis ecclesie* (Henderikx, 1987; De Bruijn, 2008). Little is known about the Medieval rural settlement development in the eastern part of the research area. The *commemoratio* mentions a villa in Odijk (*Iodichem*) as well as properties in Bunnik (*Bunnichem*) and Vechten (*Feethna*). The bishop established a farmhouse with a chapel, a so-called *curtis*, at the fort in Vechten, but this *curtis* already became abandoned during the 12th century and was left to ruin (Hessing *et al.,* 1997).

West of the city of Utrecht no rural settlements are known dating to the 9th and 10th centuries. This is probably due to the increased flooding frequency of the Oude Rijn starting in ~AD 800 onwards (Toonen *et al.,* 2013), causing unfavourable habitation conditions and concurring with a collapse around AD 850 of the Rhine-based exchange system, which has been traced dendrochronologically through the provenance of river vessels and barrels (Jansma and Van Lanen, 2016; Van Lanen *et al.,* 2016). At least one of the abandoned Early Medieval settlements west of Utrecht was partly eroded by later lateral river migration. Farm-houses were rebuilt again on the alluvial ridges in the area only from the 11th century onwards, most likely under management of the various religious Chapters stationed in the city of Utrecht (Fig. 6.8d; Van der Kamp, 2011). The Roman fort in De Meern was most likely abandoned.

Soon after the damming of the Rhine near Wijk bij Duurstede, in AD 1122, canals were dug to delimit the city and to re-establish the riverine trading and translocation routes to Utrecht (De Bruijn, 1994; Van Vliet, 2000a). Residual channels were included in this canal system (Fig. 6.8d), resulting in remarkably winding trajectories. Residual channels were also incorporated in the southern and central parts of the *novum fossatum* (the Oudegracht), and in the ~1.5 km long canal along the Hoge Weide (Fig. 6.8d; Van der Kamp, 2011).

Between AD 1134 and 1165 the estuary of the Oude Rijn silted up (Van der Linden, 1990; Parlevliet, 2001). It is likely that a sea dike was built in the former estuary to protect the hinterland area from flooding during storm surges. Subsequently, the former estuary became covered with dune sand. This silting-up can thus be linked to the loss of river discharge towards the mouth of the Oude Rijn, due to its damming upstream.

6.5 Abandonment phase stages and rise of the city of Utrecht

The combined use of geological and archaeological data leads to a phased reconstruction of the abandonment of the Utrecht river system (Fig. 6.10), which it owed to a succession of distinct processes. Abandonment of the Kromme Rijn-Oude Rijn branch, as shown by alternating stepped and gradual changes in reduced channel dimensions and altered meandering style, took over 1,000 years to complete and during this whole process, human activities concurred with the progressive abandonment. The changes of the river system strongly influenced the opportunities for human settlement and land use. People living along the river had to respond to the naturally-occurring morphological changes, not only during the Roman period when the channel was used to support and supply defensive military structures, but also during the Medieval phase of abandonment when the channel was used for trading and transport. The interaction between natural processes and human interference during the different phases of the ~1,000 year lasting abandonment of the Kromme Rijn and Oude Rijn turns out to be crucial to understand the early development of the city of Utrecht.

The observed changes in channel morphology and activity allow reconstructing relative change in discharge and variability in the channel erosive capacity (Fig. 6.10). An absolute palaeo-discharge estimate was not reconstructed. Discharge – at all stages of abandonment primarily – fluctuated naturally with peak flows as well as seasonal and yearly variability. In addition, it must have varied due to progressive avulsion and bifurcation adjustments, as is revealed by the geomorphology and sedimentary architecture of the fluvial archive. To define stages of the abandonment process, distinct changes in the fluvial archive and the derived discharge change are pin-pointed (Fig. 6.10a-c), and lined up with settlement patterns (Fig. 6.10d).

6.5.1 Mature channel belt – dispersed rural settlements (stage 0, up to ~200 BC)

During the first millennia BC, the Oude Rijn was the largest distributary of the Rhine Delta. The bankfull discharge was likely about 2,000 m^3 (2/3rd of the present Rhine bankfull discharge of 3,000-3,500 m^3; Middelkoop, 1997; Middelkoop and Van Haselen, 1999; Hesselink *et al.,* 2006; Table 6.2). The ~300 m wide river channel formed large meander bends and gradually built up a 1.5-2 km wide alluvial ridge. The formation of the Angstel-Vecht channel belt as a minor distributary hardly affected the discharge of the mature Oude Rijn (Bos *et al.,* 2009; Bos, 2010). During this phase, rural settlements were dispersed on the alluvial ridges. These settlements were built on the highest parts of the levees where they were safe from river flooding. These higher parts usually consisted of sandy clay soils, making the surrounding area suitable for cereal agriculture.

6.5.2 Waning discharge – Roman *Limes* occupation and abandonment (stage 1, ~200 BC-AD 450)

The discharge of the Rhine started to decrease substantially. This occurred firstly due to successive avulsions upstream in the delta that reduced discharge through the Rhine channel feeding the Kromme Rijn (Fig. 6.3). First, the Linge (ch.b. #97, ~2200-2000 BP) and Ravenswaay-Hollandsche IJssel channel belts (#143, #68, ~2200-2000 BP) came into existence, later followed by the Waal (ch.b. #175: ~2000 BP and ch.b. #174: ~1625 BP) and the gradually developing river IJssel (c. b. #50: ~1700 BP). In addition, the river Lek (ch.b. #191: ~1950 BP) started to develop, thereby further withdrawing discharge from the Kromme Rijn.

The decreasing discharge and a probably decreased flooding frequency increased the potential for human occupation of the alluvial ridge. However, during the Late Iron Age the number of rural settlements did not increase. After the establishment of the Roman *Limes* along the Rhine from the middle of the 1st century AD onwards, the number of rural settlements increased strongly (Fig. 6.8a) (Chapter 4; Chapter 5). When the *Limes* was abandoned in the 3rd century AD, the countryside became depopulated, and occupation was restricted to the forts (Fig. 6.8b). As the natural boundary conditions for inhabitation had not changed, the settlement decline was determined by changes in the social-economic structure – such as the disappearance of the military organisation from this region – and not related to river development.

6.5.3 River dynamics due to peak flows – re-expansion and trading network (stage 2, ~AD 450-800)

By AD 450 the channel network in the entire Rhine Delta had definitely altered (Fig. 6.3c) and the bifurcated Kromme Rijn-Oude Rijn branch had lost most of its discharge (Fig. 6.10a). Around AD 500 several of the inherited large river bends were cut off by major peak discharges that occurred in the second half of the 5th century (Fig. 6.8c). These floods probably also affected the bifurcation site by changing the angle of the channel entrance, thereby further hindering the inflow into the Kromme Rijn (cf. Kleinhans *et al.,* 2008). Because of low discharges during the subsequent period the river channel hardly changed position during the next 300 years. The discharge distribution and the oscillations between the discharge of the Oude Rijn and Vecht are difficult to reconstruct from our data, but it seems that the Vecht already captured the larger share of the discharge from this period onwards. Residual channel fills in the system may provide for more detailed discharge reconstruction in the near future (Toonen *et al.,* 2015; Cohen *et al.,* 2016).

Shortly after the river bend cut-offs in the 5th century, the alluvial ridge became inhabited again. Large rural settlements were erected on existing ridges directly along the river channel and re-activated channels. This change again must have had socio-political reasons since already before the short cut-off period the river activity was in a calm state. This settlement increase is also seen further downstream along the Oude Rijn (e.g. Hemminga *et al.,* 2006; Dijkstra, 2011; Jezeer, 2011). It is unclear what relationship these settlements had with the inhabitants of the forts. River trade flourished again in the Merovingian period, now also including North-Sea trade (e.g. Jansma and Van Lanen 2016; Van Lanen et al. 2016). From the 7th century onwards the fort in Utrecht became the seat of the Frankish settlers and a major ecclesiastical centre. Together with *Dorestad* it became a principal port of the Carolingian realm. The other forts in the area were not selected because they had lost their water supply route.

6.5.4 Final silting-up – city development and intensified land reclamation (stage 3, ~AD 800-1122)

During this stage, the transport capacity of the Oude Rijn considerably decreased, with sand bars developing in the remaining channel and on top of the former point bars, resulting in shallowing, narrowing and final silting-up of the river channel (cf. Toonen *et al.,* 2012). From the start of the 9th century AD onwards the river channel of the Oude Rijn started to form very short and sharp meander bends, i.e. with decreasing meander length and increasing meander width. This river migration might have been caused by peak flows of the Rhine. The associated floodings probably made agricultural activities very difficult and most likely also negatively influenced exchange relations with the hinterland (Van Lanen et al. 2016), leading to abandonment of all rural settlements in the area. This most likely was followed by the self-chosen exile of the Utrecht clergy after AD 857.

By AD ~1000-1150 the flooding frequency decreased, while the Oude Rijn channel became abandoned completely. The residual channel started to fill up with clay and peat. The Vecht was the larger bifurcation channel at this time. The decreasing flooding frequency enabled the bishops to return to the fort in Utrecht, resulting in the re-establishment of Utrecht as an important Medieval political and trade settlement. The settlements next to the fort and subsequently established in the countryside started to expand steadily, profiting from the large church entourage and the land release. Subsequently the silting-up stage of the river Vecht started with a likewise migration pattern.

The discharge of the Vecht seems to fade out relatively late, at the end of the 11th century or in the beginning of the 12th century AD (^{14}C-dating in Table 6.3: C13). Prior to this the Vecht still received fine-grained sediment from the Rhine during passage of peak discharge waves, whereas afterwards autochthonous organic deposition dominated the channel fill (Fig. 6.5c: Section D). This further supports the hypothesis that natural disconnection of the Kromme Rijn already had developed considerably over the centuries preceding its AD 1122 antropogenic damming at Wijk bij Duurstede. The damming affected the use of the Kromme Rhine as a shipping route to Utrecht, but the digging of canals (with locks) connecting the city of Utrecht and the river Vecht to the Lek/Hollandsche IJssel bifurcation solved this issue in the 12th century. In this manner the city could retain its regional market function. In the same period the flood basins were reclaimed by draining them with ditches and protecting the land from flooding by embankment. The reclaimed flood basins became progressively populated. Parts of these agricultural areas were incorporated in the territory of the city of Utrecht (Dekker, 1983; Henderikx, 1987; Buitelaar, 1993).

6.6 Discussion: River avulsion and settlement history

To unravel the complex interplay between river development and settlement dynamics, an interdisciplinary attitude to research opens up multiple sources of data and evidence, and provides a more comprehensive understanding of past fluvial and human settlement development. Ideally, interdisciplinary research focusing on fluvial archives from Roman and Medieval Periods should integrate geological-geomorphological data (coring, LIDAR, sections) and theory, archaeological data (excavations and surveying) and theory, historic topographic mapping and available written information analysis. Regarding the Utrecht case, the first author was actively involved in archaeological excavations and visited many such sites to collect key information on fluvial setting and channel development as summarized in Figure 6.4. This allowed complementary reconstruction of settlement characteristics, dimensions (width, depth) of (residual) channels, and the directions of channel migration in time and space *within* the channel belt.

In this section, we zoom out to the Rhine Delta at large and to some other deltas with major Roman and Medieval occupation around the Mediterranean Basin, respectively the Italian Po Delta in the Venetian-Friulian Plain and the river Arno in Tuscany, the Rhône delta in France, and the Egyptian Nile Delta (Fig. 6.11). In our comparisons of fluvial geoarchaeological patterns in lowland areas, we focus on the interaction between river development and its effect on settlement development during the Roman and Medieval periods. The central questions of this comparison are whether occupation along these rivers continued during and after channel abandonment, and what this insight can add to interpretation of the settlement history in these areas. We are aware that some of these river systems with enclosed settlements on the levees no longer were completely natural, however we have excluded more recent historical periods during which humans actively restricted flooding and channel migration by the construction of large-scale embankments, thus creating intensively river-managed situations. Moreover, we focus on large, abandoning channels because these usually take a long time to abandon completely and hence form relatively wide alluvial ridges with favourable surfaces for settlement.

6.6.1 Northwestern Europe

6.6.1.1 Rhine Delta (The Netherlands)

Within the Rhine Delta two bifurcations of importance occurred upstream of Utrecht that are relevant for the Roman and medieval situation: one at Wijk bij Duurstede (Early Medieval *Dorestad*; Fig. 6.2) and one further upstream at the delta apex, which just before the start of the Roman period shifted from a position near the city of Nijmegen (Roman *Ulpia Noviomagus Batavorum*) to its position at the Dutch-German border. The latter is the avulsion site of the rivers Waal (at Nijmegen, since around 3000 ^{14}C yr BP) and Nederrijn (at the border, since around 2500 ^{14}C yr BP). In Roman times, some 500-1,000 years after its abandonment had started, this channel belt still was characterized by open residual channels (Teunissen, 1986; Toonen *et al.,* 2012). Its alluvial ridge is considered to have been the most densely-populated part of the delta during the Roman Period (Willems, 1986; by most authors regarded as the location of the *Insula Batavorum* (Island of the Batavi) as mentioned in Tacitus'*Annales* 2,6 and *Historiae* 5, 23. Thus, similar to the Utrecht case, slow-paced abandonment and favourable settlement conditions are observed here. However, in the upper delta and in the Rhine and Meuse valleys, the development of Roman and Medieval river settlements mainly occurred on Pleistocene ice-pushed and river-terraced uplands adjacent to the Holocene flood basins. This settling along rivers and on higher Pleistocene grounds can be explained by the combination of the narrowness of the delta in this area, with the river cutting off the ice-pushed hills. Further downstream, the delta widened and such settlement locations did not exist. Therefore, the location type chosen for the Roman city of Nijmegen – founded in the upper delta on the slope of a Pleistocene ice-pushed hill (Fig. 6.3b) – contrasts with the location of the downstream delta city of Utrecht.

6.6.2 Mediterranean Region

Parallels can be drawn between the Rhine Delta and deltas along the Mediterranean Basin, because many of the Mediterranean basins in part resemble the Rhine-Meuse Delta in terms of their geomorphological and geoarchaeological setting and with regard to levels of data density and the necessity of for data integration. These basins comprise abandoned main distributaries, which predominantly were settled in Roman times and afterwards continuously were occupied, culminating in a Late Medieval embanked situation.

6.6.2.1 Venetian-Friulian Plain and Arno river (Italy)

As is the case with the Rhine-Meuse Delta, a body of literature exists describing Late Holocene geomorphology and Late Quaternary substrate for the Italian Venetian-Friulian Plain (Fig. 6.11; Adriatic Sea) occupied by the rivers Po (e.g. Marchetti, 2002; Bondesan *et al.,* 2004; Stefani and Vincenzi, 2005; Amorosi *et al.,* 2009; Stefani and Zuperelli, 2010; Bianchi *et al.,* 2014; Bruno *et al.,* 2016), Reno-Savena (Bruno *et al.,* 2013; 2015), Adige (e.g. Piovan *et al.,* 2012; Mozzi *et al.,* 2013; Corrò and Mozzi, in press), Brenta (e.g. Mozzi *et al.,* 2010; Ninfo *et al.,* 2011; Bondesan and Furlanetta, 2012), Piave (Carton *et al.,* 2009; Bondesan and Furlanetto, 2012), Tagliamento (e.g. Spaliviero, 2003; Fontana, 2006; Fontana *et al.,* 2008) and the Isonzo catchment on the eastern side of the Friulian Plain (e.g. Arnaud-Fassetta *et al.,* 2003; 2010), and cross-comparisons between

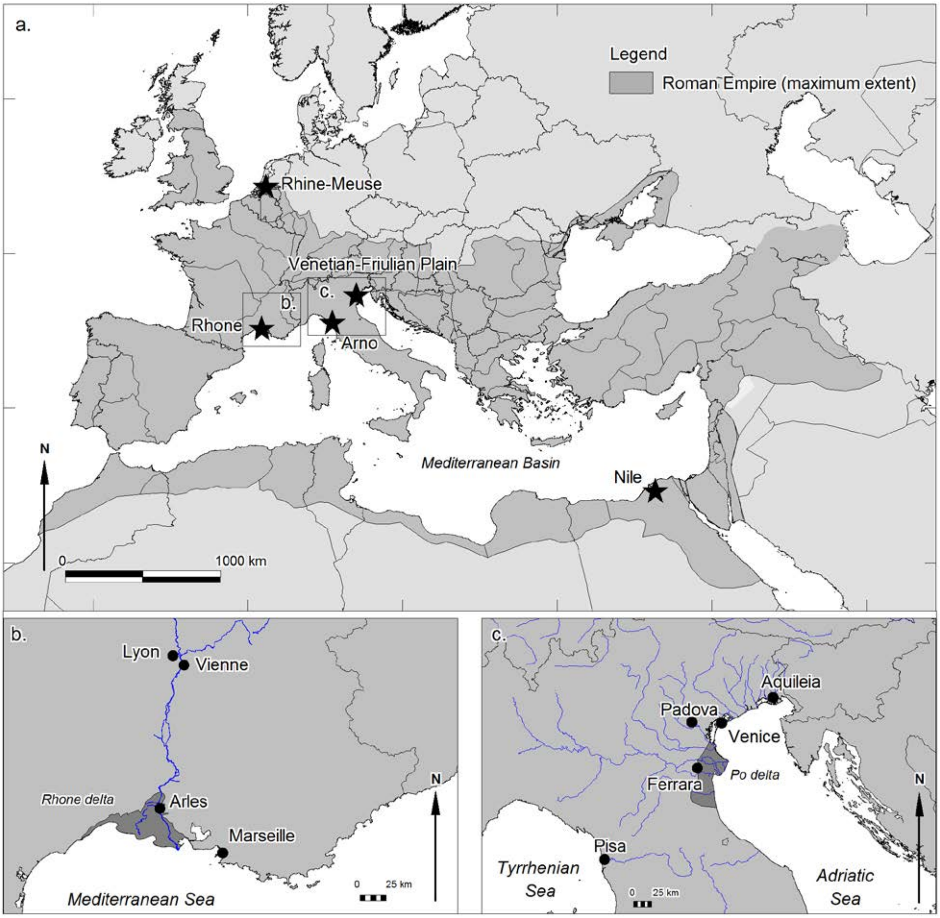


Figure 6.11 Selected Mediterranean deltas, rivers and cities with major Roman and Medieval occupation.

these rivers (e.g. Amorosi *et al.*, 2009; Fontana *et al.*, 2014; Rossato *et al.*, 2015). The parallel extends further to the archaeological data densities at the present state of research, and a long research tradition in which Holocene geological and geomorphological research interacted frequently with archaeological surveys and excavations. This also applies to the Arno coastal plain in western Italy (Aguzzi *et al.*, 2007; Sarti *et al.*, 2010; 2012; Rossi *et al.*, 2011; Amorosi *et al.*, 2013; Bini *et al.*, 2015).

The development of the cities of Ferrara, Padova and Aquileia – established along former branches of the rivers Po, Brenta and Isonzo-Torre respectively – have pre-Roman roots (except Ferrara) and subsequent city development during the Middle Ages. These therefore constitute near-ideal examples for comparison to the Utrecht case (Fig. 6.11c). The Ferrara region was well populated during the Roman period; however, it is the only city in the region not sharing a Roman or a pre-Roman origin (Amorosi *et al.*, 2009; Stefani and Zuppiroli, 2010; Bianchi *et al.*, 2014). The city nucleated in the 7th century on the northern levee of the then active river Po di Volano, at its confluence with the local river Reno and a few kilometres upstream of a major bifurcation of that period. These early phases of town formation were constricted to the shape of the natural levees of the active river. During the 12th century a new distributary channel developed flowing just north of Ferrara (Stefani and Zuppiroli, 2010). As the southern river demised in the centuries that followed, land reclamation works and protective dam construction were initiated, which enabled Ferrara to expand as a city. This development along a waning river branch, followed by land reclamation thus was remarkably similar to the Utrecht case.

The city of Padova began as an Iron Age settlement and grew to be a larger river city already in the 6th century BC (Fogolari and Chieco Bianchi, 1981; De Min *et al.,* 2005; Mozzi *et al.,* 2010). In the 2nd century BC it had become one of the most important Roman cities in northeastern Italy. It was situated on an alluvial ridge of the river Brenta. The avulsion of the river Brenta towards its modern course some 20 km upstream and the subsequent abandonment of the Padova meandering channel occurred early in the 1st millennium BC. Padova's expansion into a pre-Roman urban nucleus occurred approximately 500 years after this avulsion commenced. During the Iron Age, the spring-fed river Bacchiglione reoccupied this abandoning course of the Brenta river, sustaining water delivery to the city. The river Brenta since that time flowed north of the city (Mozzi, 2004; Bondesan and Furlanetto, 2012). As in the Utrecht case, a constant baseflow from a subordinate source (Bacchiglione) continued to supply water through the residual channels and canals long after the river abandoned, sustaining the population in this expanding delta city.

Aquileia is a major site located closer to the Adriatic Sea, along the river Isonzo. It was one of the most important fluvial harbours during Roman times (Fig. 6.11c). Human settlement of the Aquileia deltaic plain already occurred since the 6th century BC. Aquileia city was built on the outer natural levee of a meander. Upstream from Aquileia, this palaeo-channel divided into two branches (Arnaud-Fassetta *et al.,* 2003; 2010). Roman communities are known to have responded to ongoing flooding events and channel silting-up, amongst others by canalizing rivers to ensure good navigability conditions. Also, flood protection measures were taken that reduced hazards in these hydromorphous environments. Finally, at the end of the Roman Period, the role of the city in Adriatic trade exchange decreased considerably, most likely due to problems arising from the military situation, and probably also because of difficulties in navigation resulting from the increased infill of the river channel (Arnaud-Fassetta *et al.,* 2003; 2010).

The city of Pisa is located in the coastal plain of Tuscany, Western Italy (Fig. 6.11c; Tyrrhenian Sea). During the Etruscan and Roman periods in this region (resp. 7th-5th century BC and 1st century BC -2nd century AD), Pisa saw a fast urban expansion within a dense and unstable fluvial network (Sarti *et al.,* 2010; Amorosi *et al.,* 2013; Bini *et al.,* 2015). Pisa was located at the confluence of two rivers: the palaeo-Arno and the *Auser*, which was an old branch of the river Serchio. The Romans used this urban centre as a river harbour (*Portus Pisanus*). Its rivers were essential for transport and communication, and continuous river-management using hydraulic works was necessary to protect the town from floods and to prevent expansion of wetlands. Occasional floods affected the shape of the harbour. Since Etruscan times, moderately raised topography hosted the historical city centre of Pisa. Parallels may be drawn with the stages of increased overbank deposition in the Utrecht case – separating Roman from Medieval stratigraphy levels. The confluence with the river *Auser* played a crucial role in the environmental and topographic evolution of the urban area. Major parts of Pisa were characterised by poor drainage conditions until the 1st century AD, when the alluvial plain became artificially drained. Pisa remained an important commercial and political centre during the Middle Ages until it definitively passed under the domination of Florence. As was the case with *Dorestad* until the middle of the 9th century and for Utrecht until the 12th century, easy access to the sea and harbour facilities greatly favoured the economic recovery of Pisa during the Middle Ages.

These reconstructions demonstrate that socio-political and socio-economic circumstances were important factors in the timing of the expansion of settlements into larger urban centres. However, keeping a multi-phased river-abandonment succession model in mind may help to separate these cultural drivers from the evolving suitability of the landscape to host such population centres owing to fluvial geomorphological processes.

6.6.2.2 Rhône Delta (France)

Archaeological research in the Rhône Delta has revealed the establishment of numerous settlements in the deltaic plain from the 6th century BC onwards (e.g. Arnaud-Fassetta *et al.,* 2005; 2010; Arnaud-Fassetta and Landuré, 2003; Bruneton *et al.,* 2001). Predominantly built along the distributaries of the palaeo-Rhône river, these settlements consisted of temporary and/or small rural (clusters of) dwellings located on the main exchange pathways which had developed between the sea and the continent in response to the influence of the ports of Marseilles and Arles (Fig. 6.11b). During the Roman Period the number of settlements decreased significantly, which was accompanied by a marked intensification of agricultural land use (Arnaud-Fassetta *et al.,* 2010). In general, the occupation duration of settlements in this delta is considered to have depended on the functioning of a Rhône-palaeochannel (Arnaud-Fassetta and Landuré, 2003).

Lyons and Vienne are two major urban sites dating to the Roman period, the first one (*Lugdunum*) being established at the Rhône-Saône confluence and the second one (*Colonia Julia Vienna*) situated on the levee of the upper Rhône river (Fig. 6.11b). The potential vulnerability of these urban centres to flooding was minimized by building the highest points of the flood basin, and by constructing building-boulder armouring for minimising the effects of fluvial erosion.

6.6.2.3 Nile Delta (Egypt)

The geological and archaeological data density in the Egyptian Nile Delta is restricted to individual archaeological sites, and in addition these data in many cases are hard to obtain (e.g. Macklin *et al.,* 2015). Although several reconstructions of the delta development were assembled (e.g. Coutellier *et al.,* 1987; Stanley and Warne, 1993; Butzer, 2002), and even a general environmental space-time model (Pennington *et al.,* 2016), the exact distribution and development of the various Nile distributaries over time remains challenging. Numerous individual, isolated landscape studies have been carried out recently (e.g. Stanley *et al.,* 2004; Wilson, 2007; Trampier *et al.,* 2013; Graham *et al.,* 2013; 2014; 2015; Schiestl and Herbich, 2015). Yet, these investigations show that the observed changes in human behaviour and settlement patterns in the Nile Delta also need to be considered in terms of the dynamic and evolving landscape, such as avulsions, frequency of overbank floods and navigability of the river branches. As the landscape evolved, the availability and distribution of water changed, as well as the associated natural resources and transport options.

Stanley and Warne (1993) mentioned decelerating sea-level rise around 6500-5500 BC as the primary control of the initiation of farming settlements in the Nile delta, since this led to increased overbank accumulation and channel meandering. Classic historians Herodotus (2.179; 484-425/420 BC), Strabo (17.1.4; ~64 BC- AD19) and Ptolemy (100-2; AD 87-150) mentioned the presence of up to seven major distributaries of the Nile active at the same time during the Ptolemaic and Roman Periods (resp. 332-30 BC and 30 BC – AD 395; Cooper, 2014, p. 30). During these periods the western Canopic and the eastern Pelusiac Nile delta branches were main arteries for communication, trade and transport between the Egyptian Nile Valley and the Mediterranean. However the exact timing of channel activity and distribution of settlements during these periods is only roughly known. At many locations a linear distribution of ancient settlements suggests the course of ancient branches of the Nile, but detailed data on channel-belt geometry and period of activity are lacking (e.g. Trampier *et al.,* 2013; Schiestl *et al.,* 2016).

6.6.3 Water availability

In the Utrecht-Rhine case, we have mainly considered the role of the river in providing a transport and trade route, and a military border. Because in the Rhine Delta access to fresh water throughout the year is not problematic, availability of water has not been considered explicitly. During the time intervals in-between river floods, there is a difference in the source and purity of water between an active river receiving base flow from the hinterland and an open palaeo-channel with base flow from regional groundwater systems. In the temperate setting of the Rhine Delta and for Utrechts population densities during the 1st millennium AD, this difference hardly mattered (Renes, 2005). However, this difference may well have been relevant in the Mediterranean climate (especially for urban centres), and its influence probably was even larger in the semi-arid and monsoonal climate of Egypt.

6.7 Conclusion

Combined study of fluvial archives and geoarchaeology substantially improves the reconstruction of the timing and phasing of river development, and the understanding of past human settling along rivers, especially when dealing with avulsive river systems of delta plain lowlands. This is particularly the case for younger archaeological periods (classic civilisations, Medieval times, Renaissance), because of the higher find density, the accuracy of the geochronological age estimations, and limited post-depositional reworking. Late Holocene lower river reaches provide spatially extensive fluvial archives that allow studying river processes by making use of archaeological dating control. In turn, detailed reconstructions of fluvial dynamics in terms of channel belt activity and abandonment provide a better understanding of the phasing of former human occupation. The Utrecht case study of the abandonment of the river Rhine during the Roman Period and Middle Ages exemplifies how high-resolution morphological, chronological and archaeological information obtained in recent years enables to study channel morphodynamics and human settlement along a major former delta distributary branch. The work reveals the occurrence of distinct phases of geomorphological development and human settlement, and how the former influenced the latter, over a 1,000-yr period of river abandonment.

The avulsion of the Oude Rijn and Kromme Rijn occurred in three steps: 1) a ~650-yr period of slowly decreasing river discharge and limited lateral channel movement, which facilitated human settlement on the alluvial ridge; 2) a 350-yr period in which the river carried very little water, due to additional avulsions further upstream in the delta; 3) the final silting-up: a 300-yr period during which the transport capacity of the river strongly decreased, causing shallowing and narrowing of the river channel, the formation of very sharp meanders and a temporarily increase of flooding frequency. Finally, after AD 1000, the residual channel of the Oude Rijn started to collect muddy and peaty fill. Thereafter, the river became so small that it could be restrained and dammed at the avulsion node near Wijk bij Duurstede in AD 1122.

During the successive abandonment stages, people lived on the highest parts of the alluvial ridges in the study area, but they did not influence the avulsion process. The settlement history largely followed the river activity, although it was further directed by socio-economic and political factors. Only during the third phase (~AD 800-1122), the alluvial ridges were temporarily abandoned as intensified floodings most likely had a severe negative impact on agricultural activities as well an on river-based long-distance connections.

This long duration of the process of abandonment of former main branches appears to have been a common phenomenon in many deltas. During recent centuries, societies have controlled avulsions, but earlier on the abandonment aspect of avulsion appears particularly important in explaining which locations settlements became abandoned and on which locations their presence was continuous. Furthermore, as many deltas in the Late Holocene became civilisation centres and during this period only have been subjected to only one or a few avulsions, parallels can be drawn between the archaeological developments of larger sites located on top of channel belts of former rivers in different deltas.

Table 6.3 Results of ^{14}C-dates in the study area. For location and reference see Fig. 6.4 and the local data in Appendix D- Section A. The OxCal programme v4.2 (Bronk Ramsey, 2009) and the IntCal13 calibration dataset (Reimer *et al.*, 2013) were used to acquire the ages BC/AD.

C14 nr	Laboratory nr	BP ± 1ό	delta C13	Sample name	Xcoord (m)	Ycoord (m)	Sample depth (m NAP)	Ground level (m NAP)	Sample depth (cm-surface)	Sediment	Material	Alluvial ridge	Base /top/ middle	References	Remarks	Type of seed/wood
C1	GrA 18392	1940 ± 35	n.a.	Wachttoren Gemeentewerf	128910	456160	-1.05	0.45	150	clayey peat	seeds	Oude Rijn	base	Dielemans, 2014	residual channel	
C2	GrA 43211	1645 ± 35	-27.31	Laan van Chartreuse	135413	457670	-0.55	0.9	145	humic clay	seeds	Vecht	base	Den Hartog 2013c; Diependaal, 2008	swale	8 *Ranunculus acris/ repens*, 2 *Ranunculus scleratus*, 2 *Oeanthe aquatica*, 2 *Carex acuta/ ngra* type, 1 *Cirsium/ Craduus*, 1 *Lycopus europaeus*
C3	GrA 43213	1005 ± 35	-29.2	LR55-809	129858	456896	-1.75	0.05	180	humic clay	seeds	Oude Rijn	base	Den Hartog, 2010a	residual channel	
C4	GrA 43216	2200 ± 35	-30.7	LR62-568	131179	455607	-0.47	1.53	200	clayey peat	seeds	Oude Rijn	levee	Aarts, 2012	levee	
C5	GrA 43287	1385 ± 30	-27.3	LR62-699	131269	455682	-0.58	1.47	205	gyttja	seeds	Oude Rijn	base	Aarts, 2012	residual channel	
C6	GrA 43292	1610 ± 30	-24.8	LR65-22	128477	457589	-1.4	0.8	220	gyttja	seeds	Oude Rijn	base	Hoegen, 2013	residual channel	1 *Carex* sp.; 3 *Carex utricle*; 1 *Valeriana* sp.; 1 *Rumex* sp,; 1.5 *Thalictrum*
C7	GrA 43293	715 ± 30	-26.95	Marnixlaan 15	135037	457979	-0.05	1.66	171	clayey peat	seeds	Vecht	base	Den Hartog 2013b	residual channel	7 Oenanthe aquatica seeds
C8	GrA 43295	650 ± 30	-28.98	Marnixlaan 16	135104	457957	-0.24	1.66	190	humic clay	seeds	Vecht	base	Den Hartog 2013b	swale	10 Ranunculus acris/ repens, 5 Rumex spec, 1 Sambucus nigra, 1 Rubus fructicosus, 1 Cirsium/ Craduus, 1 Troliius arvensis seeds
C9	GrA 44779	1400 ± 50	-27.3	LR62-698	131269	455682	-0.28	1.47	175	clayey peat	seeds	Oude Rijn	top peat	Aarts, 2012	residual channel	
C10	GrA 50004	880 ± 35	-27.34	Twijnstraat Utrecht	136920	454920	1.50	4.6	310	sand	seeds	Oude Rijn	top	Griffioen, 2011	final stage channel deposits	Ranunculus acris/repens 2x; Stachys arvensis/ palustris 1x
C11	GrA 50882	1840 ± 100	-26.49	Zeister meander	142427	455426	0.63	1.9	127	gyttja	seeds	Zeister	base	Unpublished	residual channel	leaf remains 9x, Alnus fruit 0,5x; Phragmites australis 1x; Alisma plantago-aquatica 1x; Rumex conglomeratus 1x; Persicaria minor 1x
C12	GrA 50892	360 ± 50	n.a.	Mauritsstraat Ed Weiss I	138220	455780	-0.18	1.5	168	clayey peat	seeds	Vecht	top peat	Unpublished	residual channel	Persicaria hydropiper 4,5x, cf. embryo 2x; Polygonum aviculare 2x; Fallopia concolvulus 4x; Urtica dioica 5x; Lythtum salicaria 1x; Alisma plantago-aquatica 2x

C14 nr	Laboratory nr	BP ± 1ó	delta C13	Sample name	Xcoord (m)	Ycoord (m)	Sample depth (m NAP)	Ground level (m NAP)	Sample depth (cm-surface)	Sediment	Material	Alluvial ridge	Base /top/ middle	References	Remarks	Type of seed/wood
C13	GrA 50894	880 ± 70	-26.99	Mauritsstraat Ed Weiss III	138220	455780	-1.12	1.5	262	gyttja	seeds	Vecht	base, gyttja	Unpublished	residual channel	Rumex maritimus 1x; Rumex sp. 1x; Rumex cf. conglomeratus 1x; Salix calyptra 1x; Sonchus asper 1x; Ranunculus acris/ repens 1x; Ranunculus sceleratus 1x; Poa palustris 1x; topje met knopje van Calluna? 1x
C14	GrA 50896	560 ± 270	n.a.	Minkade Utrecht	137502	455200	2.20	2.98	78	humic clay	seeds	Vecht	base, rejected	Unpublished	rejected, error too large	Sambucus 30x fragments
C15	GrA 53568	1965 ± 40	-28.17	Fectio 300	139441	452288	-1.2	1.8	300	peaty clay	seeds	Oudwulven-broek	middle	Van den Bos et al., 2014	residual channel	
C16	GrA 55151	1900 ± 30	-28.14	Fectio 196	139441	452288	-0.16	1.8	196	peaty clay	seeds	Oudwulven-broek	top	Van den Bos et al., 2014	residual channel	
C17	GrA 55152	1940 ± 30	-29.59	Fectio 411	139441	452288	-2.31	1.8	411	gyttja	seeds	Oudwulve-broek	base	Van den Bos et al., 2014	residual channel	
C18	GrA 55196	1700 ± 30	-25.19	VLHi2 spoor 1013	129475	457645	-0.9	0.8	170	clayey peat	seeds	Oude Rijn	base	Porreij-Lyklema, 2013	residual channel	
C19	GrN 04371	2930 ± 60		Bunnik excavation	*140500*	*455400*	exact location unknown; -0.06	1.80	86		charcoal	Zeist onset		In Berendsen, 1982, 138-139: Vogel & Waterbolk 1972: 39	charcoal in vegetation horizon on clayey peat	
C20	GrN 06377	3625 ± 60		Utrecht WA 1970 Willem Arntsz	*137025*	*455195*	exact location unknown	n.a.	n.a.	n.a.	wood	Oude Rijn	n.a.	CIO Groningen database	tree in residual gully	
C21	GrN 06633	1880 ± 35		Utrecht, V&D, fuik	136305	455895	-4	4.5	850	sand	wood	Oude Rijn	in channel deposits	ABKU1926-1972, Achter Clarenburg	fish trap in channel deposits	willow
C22	GrN 11339	1565 ± 25		Visschersplein 1981	136645	455675	n.a. c. 1.50	n.a. c. 3.0	n.a. c.150	n.a.	wood	Oude Rijn		ABKU 1981; CIO Groningen database	wooden pallisade along residual channel	
C23	GrN 11340	2200 ± 80		Pieterskerkhof 10-11	137055	455930	c.1.0	3	c. 200	n.a.	charcoal	Oude Rijn		ABKU 1982	levee	
C24	GrN 11341	1930 ± 50		Pieterskerkhof 10-11	137055	455930	c. 0.7	3	c. 230	n.a.	charcoal	Oude Rijn		ABKU 1982	levee	
C25	GrN 11342	1240 ± 25		Utrecht Oudkerkhof skelet	136770	456020	-2.4	n.a.	n.a.	n.a.	bone	Oude Rijn		ABKU 1976-77; CIO Groningen database	inhumation	
C26	GrN 13709	1205 ± 25		Utrecht boat 1-1	135040	457955	n.a.	n.a.	n.a.	n.a.	wood (from boat)	Oude Rijn		CIO Groningen database	river migration	
C27	GrN 17542	1845 ± 50		Mare I	130390	453650	-4.20	-0.70	350		bone	De Mare/ Heldam		Berendsen, 1990	residual channel	
C28	GrN 18106	4135 ± 40		Vechten 2	140637	452635	0.60	2.40	180		wood and leaves	Werkhoven	base	Berendsen & Wynia 1993	in sandy channel fill	
C29	GrN 18107	2590 ± 70		Vechten 3	140640	452567	1.00	2.40	140		wood	Houten	base	Berendsen & Wynia 1993	in sandy channel fill	

C14 nr	Laboratory nr	BP ± 1ó	delta C13	Sample name	Xcoord (m)	Ycoord (m)	Sample depth (m NAP)	Ground level (m NAP)	Sample depth (cm-surface)	Sediment	Material	Alluvial ridge	Base /top/ middle	References	Remarks	Type of seed/wood
C30	GrN 20345	1210 ± 25		Utrecht Waterstraat 1	*136315*	*456405*	exact location unknown	n.a.	n.a.	n.a.	wood (from boat)	Vecht		Van de Moortel, 2009	dendro late 10th, river migration	
C31	GrN 20346	1198 ± 23		Utrecht Waterstraat 2	*136315*	*456405*	exact location unknown	n.a.	n.a.	n.a.	wood (from boat)	Vecht		Van de Moortel, 2009	dendro late 10th, river migration	
C32	GrN 20942	940 ± 40		Utrecht Lange Lauwerstraat moss	136655	456410	n.a.	n.a.	n.a.	n.a.	wood (from boat)	Vecht		Van de Moortel, 2009	river migration	
C33	GrN 20945	1090 ± 30		Utrecht Waterstraat 3	*136315*	*456405*	exact location unknown	n.a.	n.a.	n.a.	wood (from boat)	Vecht		Van de Moortel, 2009	dendro late 10th, river migration	
C34	GrN 22748	5520 ± 35		Vechten-De Mast M2	140029	451506	-4.1	1.60	570	Peat on E/TF	peat	GW-level	base	Berendsen & Stouthamer 2001	GW-level	
C35	GrN 22822	5400 ± 35		Vechten-De Mast M2	140029	451506	-4.1	1.60	570	Wood in peat on E/TF	wood	GW-level	base	Berendsen & Stouthamer 2001	GW-level	
C36	KIA 37442	3065 ± 25	-26.8	LR57-144	130967	455691	-0.33	0.87	120	gyttja	wood	Oude Rijn	base	Meijer, 2009	landing-stage in residual gully	
C37	KIA 37443	3030 ± 30	-26.6	LR57-174	130966	455690	-0.83	0.87	170	gyttja	wood	Oude Rijn	base	Meijer, 2009	landing-stage in residual gully	
C39	KIA 37444	3075 ± 30	-19.2	LR57-212	130975	455686	-1.2	0.8	200	gyttja	bone, collagen	Oude Rijn	base	Meijer, 2009	residual channel	
C40	KIA 37445	3010 ± 30	-21.6	LR57-246	130994	455692	-0.5	0.8	130	gyttja	bone, collagen	Oude Rijn	base	Meijer, 2009	residual channel	
C41	KIA 43434	3555 ± 25	-26.3	LR67-27	132715	453740	-1.05	0.08	113	clayey peat	seeds	Oude Rijn	base	Dielemans, 2103b	residual channel	Carex nutlet (4), Conium maculatum (24), Stachys sylvatica (3), Solanum nigrum (17), Carex hirta/riparia (2), Carex sp charred (1), Mentha aquatica/arvensis (19), Brassicaceae (1
C42	KIA 43435	3600 ± 30	-26	LR67-137B	132620	453940	-1.85	0.1	195	gyttja	seeds	Oude Rijn	base	Dielemans, 2103b	residual channel	Stachys (1), Carex hirta/riparia (5), Carex acuta type (2), Carex nutlet (2), Mentha aquatica/arvensis (1), Alisma plantago-aquatica (1), Poaceae (7), Papaver sp (1), cf. Carum ventriculatum (2), Salix sp. knopje (1), Typha sp. (1)
C43	KIA 49507	1850 ± 30	-25.3	UTRT2-10-177	136980	455840	0.5	2	150	peaty clay	seeds	Oude Rijn	base	Van Benthem, in press.	swale	
C44	Poz 20984	1810 ± 30	-32.1	V239, S149, schelpenpad	138970	451920	0.6	1.3	70		wood underneath path of shells	Oudwulven-broek	base ~start residual	Heiden & Koot, 2009	next to residual channel	
C45	Poz 20986	960 ± 30	-28.8	V339, S174, restgeul B	139000	451833	-0.2	1.6	180		wood		middle	Heiden & Koot, 2009	residual channel	

C14 nr	Laboratory nr	BP ± 1ó	delta C13	Sample name	Xcoord (m)	Ycoord (m)	Sample depth (m NAP)	Ground level (m NAP)	Sample depth (cm-surface)	Sediment	Material	Alluvial ridge	Base /top/ middle	References	Remarks	Type of seed/wood
C46	Poz 20987	1890 ± 30	-28	V278 S149, schelpenpad	138970	451920	0.6	1.3	70		wood underneath path of shells	Oudwulven-broek	base ~start residual	Heiden & Koot, 2009	next to residual channel	
C49	Poz 20988	1750 ± 30	-28.6	V43, S8, restgeul A	138985	451880	0.5	1.3	80		wood	Oudwulven-broek	top	Heiden & Koot, 2009	pole in residual channel	
C50	Poz 21012	870 ± 30	-22.2	V396, S168.2, restgeul B	139000	451833	-0.2	1.6	180		bone		middle	Heiden & Koot, 2009	residual channel	
C51	SUERC 27873	1050 ± 30	-28.9	LR65-15	128355	457590	-1.2	0.9	210	gyttja	seeds	Oude Rijn	base	Hoegen, 2013	residual channel	Persicaria lapathifolia, Ranunculus acris/repens, Polygonum aviculare, Stellaria media
C52	SUERC 27874	1070 ± 30	-28.9	LR65-134	128755	457690	-1	0.7	170	gyttja	seeds	Oude Rijn	base	Hoegen, 2013	residual channel	Persicaria lapathifolia, Ranunculus acris/repens, Polygonum aviculare, Stellaria media
C53	SUERC 30355	1950 ± 35	-25.6	AML 188	135024	453886	-0.7	0.1	80	clay	wood	Oude Rijn	top	Dieleman & Van der Kamp, 2012	post in residual channel	oak
C54	SUERC 30356	3940 ± 35	-26.7	AML 069	135018	453900	-0.1	0.1	20	clay	wood	Oude Rijn		Dieleman & Van der Kamp, 2012	trunk in channel deposits	oak
C55	SUERC 30357	2305 ± 35	-27.2	AML 110	135006	453895	-1	0.1	110	clay	wood	Oude Rijn	middle	Dieleman & Van der Kamp, 2012	eel-buck in residual channel	willow
C56	SUERC 30358	1910 ± 35	-25	AML 059	135015	453889	-0.5	0.1	60	clay	wood	Oude Rijn	top	Dieleman & Van der Kamp, 2012	trunk in channel deposits	oak
C57	SUERC 30667	3075 ± 30	-34	AML 071	135013	453893	-1.7	0.1	180	clayey peat	seeds	Oude Rijn	base peat	Dieleman & Van der Kamp, 2012	residual channel; high delta C13 value	*Oenanthe aquatica*, *Carex* spec, *Schoenoplectus lacustris*, *Alopecuris geniculatus*
C58	SUERC 30668	2500 ± 30	-25	AML 073	135013	453893	-1.28	0.1	138	clayey peat	seeds	Oude Rijn	top peat	Dieleman & Van der Kamp, 2012	residual channel	*Oenanthe aquatica*, Laminaceae, *Ranunculus scleratus*, *Solanum nigrum.*
C59	SUERC 40863	3200 ± 35	-25.2	DSL-31	136713	452959	-0.4	1	140	peat	seeds	Oude Rijn	top peat	Dielemans, 2014	residual channel	1 Carex acuta/nigra type, 2 Schoenoplectus lacustris, 1 Atriplex patula/prostrate, 4 Chenopodium album, 1 Persicaria minor, 7 Solanum nigrum, 2 Stellaria media, 2 Carduus cf. Crispus, 1 Plantago major, 1Polygonum aviculare, 1 Rumex crispus type, 14 Ranunculus acris/repens, 1 Hordeum vulgare
C60	SUERC 40864	3415 ± 35	-25.8	DSL-33	136713	452959	-1	1	200	humic clay	seeds	Oude Rijn	base	Dielemans, 2014	residual channel	1 Carex hirta/riparia type, 2 Mentha aquatica/arvensis, 1 Ranunculus sp., 14 Schoenoplectus lacustris, 1 Persicaria minor

C14 nr	Laboratory nr	BP ± 1ó	delta C13	Sample name	Xcoord (m)	Ycoord (m)	Sample depth (m NAP)	Ground level (m NAP)	Sample depth (cm-surface)	Sediment	Material	Alluvial ridge	Base /top/ middle	References	Remarks	Type of seed/wood
C61	SUERC 40865	3475 ± 35	-30.9	DSL-109	136705	452928	-0.2	1	120	sitly clay	wood	Oude Rijn		Dielemans, 2014	>35 m long wicker work (fence) in final phase of channel deposits	willow
C62	SUERC 41368	1770 ± 30	-26.1	Zeist-11-94: 28-32	144780	455040	c. 4	5.0	c. 100	peaty clay	seeds	Zeist	base	Vermue & Molthof, 2014	crevasse channel	various Cyperaceae taxa
C63	SUERC 41369	1270 ± 30	-26.1	Zeist-11-94: 16-20	144780	455040	c. 4.12	5.0	c. 88	peaty clay	seeds	Zeist	top	Vermue & Molthof, 2014	crevasse channel	Carex and Ranunculus
C64	SUERC 53120	2027 ± 24	-28.1	LR84-121	132959	456426	-0.8	0.6	140	humic clay	wood	Oude Rijn crevasse		Den Hartog in prep. b	pole in crevasse channel	
C65	SUERC 53121	1983 ±26	-27.3	LR84-122	132958	456429	-1	0.6	160	humic clay	wood	Oude Rijn crevasse		Den Hartog in prep. b	pole in crevasse channel	
C66	SUERC 53122	2167 ± 27	-27.5	LR84-208	132960	456418	-1	0.6	160	humic clay	wood	Oude Rijn crevasse		Den Hartog in prep. b	pole in crevasse channel	
C67	SUERC 54219	1772 ± 30	-25	LR84-41	*132657*	*456420*	-0.9	1	190	peaty clay	seeds	Oude Rijn crevasse	top peat	Den Hartog in prep. b	residual channel	
C68	SUERC 54220	1981 ± 30	-28.6	LR84-43	*132657*	*456420*	-1.28	1	228	peaty clay	seeds	Oude Rijn crevasse	base	Den Hartog in prep. b	residual channel	
C69	Ua 36484	1640 ± 35	-29.7	LR55-802	129833	456995	-0.7	0.55	135	gyttja	seeds	Oude Rijn	base	Den Hartog, 2010a	start medieval channel depsoits/ late roman residual channel	Salix remains
C70	UtC unknown	1610 ± 30	n.a.	Pieterskerkhof graves	137045	455930	n.a.	n.a.	n.a.		bone			De Groot, 1991	burial	
C71	UtC 06948	3103 ± 34	34	Heldammer 256	129400	454910	-1.5	-0.2	130	peat	seeds	Heldam crevasse channel	Alnus peat	Cohen et al., 2012	crevasse channel, overlying Phragmites peat	26 Carex rostrata, 33 Typha, 14 Mentha aquatica, 1 Oenanthe aquatica, 1 Alisma plantago aquatica (Top of Alnus peat overlying Phragmites peat and gyttja)
C72	UtC 06975	3830 ± 90	90	Heldammer 255	129400	454910	-1.87	-0.2	167	peat	seeds	Heldam crevasse channel	Phragmites peat	Cohen et al., 2012	crevasse channel	5 Sagittaria sagittifolia, 2 Oenanthe aquatica, 2 Carex sp., 2 Potentilla, 1 Ranunclus scleratus (Phragmites peat)
C73	UtC 06978	1930 ± 60	n.a.	Schip De Meern 1	129843	454807	0.45	1.85	140	humic clay	seeds	Heldam 2	base	Van Dinter & Graafstal, 2007	residual channel	
C74	UtC 10334	1414 ± 48	-34.4	LR8 sleuf 10	132633	456133	-1	0.95	191-200	humic clay	seeds	Oude Rijn	base	Berendsen & Stouthamer, 2001	residual channel	
C75	UtC 11139	1774 ± 35	-29.9	Zeist PTT-2	144880	454752	3.12	4.5	138-140	gyttja-peat	seeds	Zeist	base	Cohen et al., 2012	residual channel	
C76	UtC 11184	3973 ± 38	-25.7	Heldam 6 7-39-375	128759	455762	-3.51	0.2	369-371	peaty clay	seeds	Heldam		Berendsen & Stouthamer, 2001	onset Oude Rijn; levee deposits in floodbasin	

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C77	UtC 11183	4221 ± 37	-25.4	Heldam 5 7-39-311	128759	455762	-2.85	0.2	300-320	peaty clay	seeds	Heldam		Berendsen & Stouthamer, 2001	1th onset Heldam; levee deposits in floodbasin	
C78	UtC 11182	4053 ± 43	-25.6	Heldam 4 7-39-270	128759	455762	-2.5	0.2	260-280	peaty clay	seeds	Heldam		Berendsen & Stouthamer, 2001	1th ending Heldam; levee deposits in floodbasin	
C79	UtC 11181	3840 ± 45	-24.6	Heldam 3 7-39-226	128759	455762	-2.06	0.2	220-245	peaty clay	seeds	Heldam		Berendsen & Stouthamer, 2001	2nd onset; levee deposits in floodbasin	
C80	UtC 11180	3465 ± 41	-24.7	Heldam 2 7-39-193	128759	455762	-1.73	0.2	175-200	peaty clay	seeds	Heldam		Berendsen & Stouthamer, 2001	2nd ending Heldam; levee deposits in floodbasin	
C81	UtC 11179	2907 ± 31	-25.5	Heldam 1 7-39-150	128759	455762	-1.3	0.2	140-165	peaty clay	seeds	Heldam		Berendsen & Stouthamer, 2001	3td onset Heldam: levee deposits in floodbasin	
C82	UtC 11990	4444 ± 38	-28.1	Heldam 7	128459	455762	-3.47	0.2	367	peat	seeds	Heldam		Berendsen & Stouthamer, 2001	Final date of first phase Oude Rijn	
C83	UtC 11991	4990 ± 45	-28	Heldam 8	128459	455762	-3.62	0.2	382	peat	seeds	Heldam		Berendsen & Stouthamer, 2001	GW-level	
C84	UtC 12175	952 ± 28	-23	LR36-3	132626	456200	-1.4	1	240	clayey peat	seeds	Oude Rijn	base	Van der Kamp, in prep. b/ Den Hartog, in prep. b	residual channel	cereal grain
C85	UtC 12176	1190 ± 70	-30	LR36-15	132333	456518	-3.04	1	404	clayey peat	seeds	Oude Rijn	base	Van der Kamp, in prep. b/ Den Hartog, in prep. b	residual channel	uncharred plant remains
C86	UtC 12429	1846 ± 31	-28.2	DMN-120 schip NISA de Meern 1	129855	454800	-2.03	1.17	320	humic clay	seeds	Heldam 2	base	Van Dinter & Graafstal, 2007	residual channel	
C87	UtC 13086	3142 ± 33	-26.7	LR39-3	130050	454760	1.17	4.37	320	gyttja	seeds	Heldam 1	base	Langeveld & Luksen-IJtsma, 2010	residual channel	
C88	UtC 13249	2733 ± 37	-30.9	LR39-1	130050	454756	-0.9	1.2	210	clayey peat	seeds	Heldam 1	top peat	Langeveld & Luksen-IJtsma, 2010	residual channel	3 *Alisma plantago-aquatica*, 1 *Carex vesicaria*, 3 *Eleocharis palustris*, 6 *Hypericum* cf. *perforatum*, *1 Mentha aquatic*, *1 Oenanthe aquatic*, *2* Poaceae, 1 *Poa* sp., 1 *Polygonum* cf. *minus*, *1 Rorippa palustris*, *1 Scrophularia* cf. *umbrosa*

C14 nr	Laboratory nr	BP ± 1ó	delta C13	Sample name	Xcoord (m)	Ycoord (m)	Sample depth (m NAP)	Ground level (m NAP)	Sample depth (cm-surface)	Sediment	Material	Alluvial ridge	Base /top/ middle	References	Remarks	Type of seed/wood
C89	UtC 13250	3082 ± 38	-29.4	LR39-2	130050	454756	-1.6	1.2	280	clayey peat	seeds	Heldam 1	base peat	Langeveld & Luksen-IJtsma, 2010	residual channel	2 *Carex* sp.*, 1* Cruciferae/ *Galium*?, 2 *Phagmites australis, 2 Rumex* sp.
C90	UtC 13251	1935 ± 27	-26.6	LR42-3	132964	456491	-1.45	0.7	215	mollusc layer	seeds	Oude Rijn	base	Den Hartog, 2009	residual channel	1 Sambucus sp., 6 Solanum dulcamara
C91	UtC 13315	1557 ± 37	-28.3	t Zand-2	132477	456543	-1.27	0.78	205	clayey peat	seeds	Oude Rijn	base peat	Jansen & Leijnse, 2005	residual channel	5 *Atriplex* sp., *2 Chenopodium* sp., *2 Epilobium hirsutum, 1 Polygonum* cf *lapathifolium, 5 Ranunculus* cf. *acris/ repens*, 4 *Ranunculus* sceleratus, 2 *Stellaria media*, 1 *Urtica dioica*
C92	UtC 13357	1315 ± 33	-27.6	t Zand-1	132477	456543	-1.03	0.78	181	clayey peat	seeds	Oude Rijn	top peat	Jansen & Leijnse, 2005	residual channel	*7 Alisma plantago-aquatica, 1 Carex* sp., 3 *Oenanthe aquatic*, 1 *Ranunculus* cf. *acris/repens, 5 Salix* sp., 1 *Sonchus* sp.
C93	UtC 13358	1615 ± 31	-26.7	LR42-1	132964	456491	-0.97	0.7	167	clayey peat	seeds	Oude Rijn	top peat	Den Hartog, 2009	residual channel	1 Carduus/Cirsium, 1 Chenopodium sp., 1 Compositae, 1 Polygonum cf lapathifolium, 2 Ranunculus cf. acris/ repens, 5 Rumex sp., 1 Solanum dulcamara, 1 Sonchus sp., 1 Stellaria medi, 1 Urtica dioica, 1 Valeriana sp.
C94	UtC 13359	1792 ± 31	-24.8	LR42-2	132964	456491	-1.31	0.7	201	gyttja	seeds	Oude Rijn	base	Den Hartog, 2009	residual channel	1 Berula erecta, 5 Carex sp. nutlet, 1 Carduus/ Cirsium, 1 Eleocharis palustris, 3 Phagmites australis, 1 Solanum dulcamara,
C95	Utc 14930	2546 ± 33	-23	LR57-060	130982	455688	-1.28	0.02	130	clayey peat	seeds	Oude Rijn	top peat	Meijer, 2009	residual channel	*Phragmites australis*
C96	UtC 14931	2821 ± 32	-23.9	LR57-100	130982	455688	-1.68	0.02	170	clayey peat	seeds	Oude Rijn	base peat	Meijer, 2009	residual channel	*Phragmites australis*
C97	UtC 14932	2134 ± 30	-27.2	LR57-099	131168	455699	-1	0.5	150	sandy clay	wood	Oude Rijn	active	Meijer, 2009	post in channel; active	
C98	UtC 14933	792 ± 27	-24.6	Croeselaan – Rabobank	135945	455275	-0.6	2.4	300	gyttja	seeds	Oude Rijn	base	Unpublished	residual channel	
C99	UtC 14934	2491 ± 33	-27.8	Lombok	135560	456055	-0.8	2.2	300	humic clay	seeds	Oude Rijn	base	Den Hartog, 2013	residual channel	*Salix 3 bud, Rumex maritimus/palustris; Rumex sp., Persicaria hydropiper 2, Persicaria lapathifolia, Carex acuta/elata, Cirsium arvense/palustre 2 fruits, Atriplex patula/prostata fruit, Ranunculus scleratus seed*

C14 nr	Laboratory nr	BP ± 1ó	delta C13	Sample name	Xcoord (m)	Ycoord (m)	Sample depth (m NAP)	Ground level (m NAP)	Sample depth (cm-surface)	Sediment	Material	Alluvial ridge	Base /top/ middle	References	Remarks	Type of seed/wood
C100	UtC 14935	1821± 34	-26.9	PK5100 Pieterskerkhof	136960	455950	2.15	4.15	200	humic clay	charcoal	Oude Rijn	base	Luksen-IJtsma, 2010	residual channel	
C101	UtC 14936	2761 ± 33	-24.3	LR52	129085	459020	-0.9	0.5	140	clayey peat	seeds	Oude Rijn	?	Unpublished	residual channel	Phragmites
C102	UtC 14937	912 ± 28	-27.4	Ahornstraat-8	135530	457130	-0.4	1.7	210	gyttja	seeds	Vecht	base	Den Hartog, 2013b	residual channel	*Triticum dicoccon*, *Rumex acetosela*, *Rumex hydrolapathum*, *Rumex palustris*, *Stellaria media*, *Ranunculus scleratus*
C103	UtC 15137	2481 ± 30	-28	LR55-19	129640	457025	-1	0.7	170	clayey peat	seeds	Oude Rijn	base	Den Hartog, 2010a	residual channel	Salix seed
C104	UtC 15138	3815 ± 30	-23.6	LR60-21	131603	454530	1.78	2.15	37	silty clay	charcoal	crevasse-complex Heldam 1		Weterings & Meijer, 2011	top levee	
	Houten final phase, T8															
C105	GrA 23920	2230 ± 40	-20.07	HOUN03-VNR1180	141193	448059	2.5	0.45	215		bone	Houten	base	Dijkstra & van Benthem, 2004	burial at edge of residual channel	
C106	KIA 22134	2149 ± 37	-29.51	HOUN03-VNR1442MP	141210	448055	2.5	1.05	100		seeds	Houten	base	Dijkstra & van Benthem, 2004	residual channel	
	Houten final phase, T14															
C107	GrN 26049	2070 ± 45	-25.88	HTNV000035	141220	446900	c. 1.5	2.3	c. 80		charcoal	Houten last phase	middle	Krist et al., 2001	residual channel	
C108	GrN 26050	2040 ± 45	-27.73	HTNV000076	141220	446900	c. 1.5	2.3	c. 80		charcoal	Houten last phase	middle	Krist et al., 2001	residual channel	
C109	GrN 26051	2070 ± 20	-27.56	HTNV00823	141220	446900	c. 1.5	2.3	c. 80		wood	Houten last phase	middle	Krist et al., 2001	residual channel	
C110	GrN 26095	1990 ± 30	-25.87	HTN000820	141220	446900	c. 1.5	2.3	c. 80		wood	Houten last phase	middle	Krist et al., 2001	residual channel	
C111	GrA 17490	2250 ± 50	-21.03	HTNV000180	141220	446900	c. 1.5	2.3	c. 80		bone	Houten last phase	middle	Krist et al., 2001	burial at edge of residual channel	
	Wijk bij Duurstede															
C112	KIA 44269	1765 ± 35	-29.74	WIJD-07 2674	152074	443085	2.03	5.1	307	humic clay	seeds	seeds	base	Dijkstra, 2012	residual channel	
C113	SUERC-42607	1864 ± 26	-25	WIJD3-10 1198-93	151460	443965	2.54	5	246	humic clay	seeds	Kromme Rijn	base	Williams, 2004	residual channel	Salix, Rumex
C114	SUERC-42608	1589 ± 29	-26.9	WIJD3-10 1199-47	151460	443965	3	5	200	humic clay	seeds	Kromme Rijn	top	Williams, 2004	residual channel	Schoenoplectus lacustris, Alisma plantago-aquatica
C115	SUERC-42609	1710 ± 26	-24.7	WIJD3-10 603-45,5	151667	443861	3.1	5	190	humic clay	seeds	Kromme Rijn	base	Williams, 2004	residual channel	Schoenoplectus lacustris

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	Oude Rijn downstream															
C116	UtC 11987	2653 ± 45	-27.8	Oude Rijn 1	123912	458047	-1.85	-1	85	peat	seeds	Oude Rijn	Kromme Rijn-Oude Rijn (last phase)	Berendsen & Stouthamer, 2001	levee in flood basin deposits	
C117	UtC 11988	2683 ± 42	-28.8	Oude Rijn 2A	123912	458047	-2.8	-1	180	gyttja	seeds	Oude Rijn	Final phase Houten-Oude Rijn	Berendsen & Stouthamer, 2001	levee in flood basin deposits	
C118	UtC 11989	3625 ± 37	-28.5	Oude Rijn 3A	123995	457855	-4.09	-0.85	324	peat	seeds	Oude Rijn	First large-scale activity of Houten-Oude Rijn	Berendsen & Stouthamer, 2001	levee in flood basin deposits	

Table 6.4 Results of OSL-dated samples in the study area. Sample O8 is based on single grain analysis. For locations see Fig. 6.4 and Appendix D- Section A.

Nr.	Laboratory nr	OSL ± 1SD	Sediment	Sample name	Xcoord	Ycoord	Zcoord (m OD)	Surface (m OD)	Depth sample (cm)	Inter-pretation	References	PaleoDose (Gy)	Dose rate (Gy/ka)	Remarks
O1	Oxford X3017	1750 ± 150 before 2007	sand	UTDH-339	136610	455499	1.86	4.3	244	Washover/ flooding layer	Duurland, in press	3.04 ± 0.12	1.73 ± 0.12	Dated layer covers roman graves dating until first half of 3rd century AD
O2	Oxford X3529	1830 ± 360 before 2009	sand	LR65-M14	128745	457623	-0.2	1.2	140	Channel deposits	Hoegen, 2013	3.67 ± 0.64	2.01 ± 0.23	
O3	Oxford X3530	2370 ± 370 before 2009	sand	LR65-M15	128741	457602	0	1.35	135	Channel deposits	Hoegen, 2013	3.90 ± 0.42	1.65 ± 0.19	
O4	Oxford X3743	1420 ± 135 before 2009	silty clay	UTRT-63	136475	456260	1.59	4	241	Washover/ flooding layer	Verniers, 2010	2.75 ± 0.16	1.94 ± 0.14	High concentrations of thorium and uraniu (~ x 3 as X3874)
O5	Oxford X3874	2600 ± 310 before 2010	sandy clay	UTRT2-30	136130	456030	0.6	2.3	170	Washover/ flooding layer	Bouma, 2011	3.14 ± 0.18	1.34 ± 0.09	Partial bleaching not excluded
O6	Risø 082104	5350 ± 310 before 2008	sand	LR57-429	130993	455708	-0.4	0.85	125	Channel deposits	Meijer, 2009	8.11 ± 0.31	1.51 ± 0.06	Rejected, too old, stratigraphically impossible
O7	NCL 7110025	1700 ± 151 before 2011	silty clay	UTKE-OSL3	135050	454700	0.3	1.5	120	Levee deposits	Briels, 2011; Wallinga & Johns, 2011	4.95 ± 0.41	2.91 ± 0.09	
O8	NCL 7110026	2330 ± 151 before 2011	silty clay	UTKE-OSL4	135050	454700	-0.15	1.5	165	Channel deposits	Briels, 2011; Wallinga & Johns, 2011	5.91 ± 0.20	2.53 ± 0.15	
O9	NCL 7614044	2060 ± 130 before 2013	sand	BAAC-Ganze-nmarkt_vnr.167	136664	456065	1.38	5.2	382	Top pointbar	Van der Mark, in prep.	4.20 ± 0,20	2.01 ± 0,08	

Table 6.5 Overview of dimensions (width and depth) used for the reconstruction of active channel and residual channel dimensions (values in bold are those used for calculations in Fig. 6.9) and age-control. For references see Appendix D – Section A, for locations see Appendix D – Section B and Fig. 6.4.

		Residual channel			Channel deposits		Dating	14C Dating nr	Archaelogical finds	Reference
Section	Channel belt	Width (m)	Depth (m)	Base (m OD)	Base (m OD)	Base (m below surface)				
A	Zeist	**115**	2	-1	-6	**-8**	Roman	GrA 50882	no finds	Van Munster, 2012
B1 (section C)	Oudwulvenbroek	**110**	**7**	-6	-	-	Roman	GrA 53568, GrA 55151, GrA 55152	Roman	Jansen et al., 2014; Van den Bosch et al., 2014
B2 (section A)	Oudwulvenbroek	**130**	5	-3.5	-	-	id.		Roman	Jansen et al., 2014; Van den Bosch et al., 2014
C.	Oudwulvenbroek	>30	2	-1.3	-	-	probably Roman		no finds	Warning, 2008; Verniers & Van Dinter, 2011
D	Vecht	**50** (old ditch pattern)	1.5	-1.1	-	-	Late medieval	GrA 50894	Late medieval	Unpublished
E	Oude Rijn	-			-	-	Late medieval river movement	GrA 50004	no finds	Griffioen, 2011
F	Oude Rijn	5	1.5	-0.3	-	-	Late medieval	UtC 14935	Late medieval	Van Veen, 2010
G	Oude Rijn	-	-	-	-	-	Late medieval river movement		Late medieval	Den Hartog 2013a
H1	Oude Rijn	-	-	-	-	-	Roman river edge		Roman	Luksen-IJtsma, 2010
H2	Oude Rijn	-	-	-	-	-	post Roman river activity	GrN 11340; GrN 11341	Early Medieval	ABKU 1982: Pieterskerkhof 10-11
H3	Oude Rijn	-	-	-	-5,5	**-7**	pre Roman; probably Late Iron age		no finds, but below Roman fort	Kloosterman & Hoegen, in prep.
I1	Oude Rijn	**165-180**	>3.5	>-2	-	-	pre Early medieval; probably Roman		no finds	Kalisvaart, 2012b; Van Mousch, in prep.
I2	Oude Rijn	22	2	0	-	-	Late Medieval		re-deposited roman and early medieval finds; late medieval finds in vegetation horizon	ABKU 1926-1972: Achter Clarenburg; Dominicus & Van den Berg, 1971
I3	Oude Rijn	5	1.5		-	-	Early medieval	dendrodate UT 600010-60	Early Medieval	Jansma 2013; Van Mousch, in prep.
I4	Oude Rijn	-			-	-	Early medieval river movement		Early Medieval	AKPU 2004 2005: Rijnkade
J	Oude Rijn	10	2	-	-	-	Late medieval	UtC 14933	no finds	Unpublished; Van Deventer 1569; Verstralen 1629
K	Oude Rijn	10	1.5	-0.2	-	-	Late medieval		Late medieval	Den Hartog 2013a
L1	Oude Rijn	-	-	-	-	-	Early medieval incision and late medieval river movement		Early medieval settlement; Late medieval	Nokkert et al., 2009

		Residual channel			Channel deposits		Dating	14C Dating nr	Archaelogical finds	Reference
Section	Channel belt	Width (m)	Depth (m)	Base (m OD)	Base (m OD)	Base (m below surface)				
L2	Oude Rijn	10	2	-	-	-	Late medieval		Late medieval	Nokkert et al., 2009
M1	Oude Rijn	>8	~ 4	-3.1	-	-	Late medieval	UtC 12176	Late medieval	App. in Den Hartog, in prep. b or in Van der Kamp, in prep. b
M2	Oude Rijn	13	2	-1.3	-	-	Late medieval		Late medieval	App. in Den Hartog, in prep. b or in Van der Kamp, in prep. b
M3	Oude Rijn	20	2	-1.25	-	-	Late medieval	UtC 12175	Late medieval	App. in Den Hartog, in prep. b or in Van der Kamp, in prep. b
M4	Oude Rijn	10	2	-1.9	-4.4	-5.2	early Roman	UtC 13315; UtC 13357; SUERC 54219; SUERC 54220	no finds	Jansen Leijnse, 2005; Den Hartog in prep. b
N phase a	Heldam	**70-100 ***	-	-	4	**-3.5**	Roman: 1st c.		Roman	Aarts, 2012
N phase b	Heldam	40-50 *	-	-	2.5	-2	Roman: start 3rd c.		Roman	Aarts, 2012
N phase c = 2B	Heldam	10	1	-1	-	-	Roman: mid 3rd c.		Roman	Aarts, 2012; Jongkees & Isings, 1963
O phase 2	Heldam	**35-45**	**4.5-5**		-	-			Roman	Aarts, 2012
O phase 2B	Heldam	8	1	-2	-	-	Roman: mid 3rd c.	UtC 12429; UtC 06978	Roman	Van Dinter & Graafstal, 2007
P phase 2	Heldam		-	-	-6	**-7**			Roman	Nales & Vis, 2003
P phase 2B	Heldam	8	1	-2	-	-	Roman: mid 3rd c.		Roman	Dielemans, 2014a
Q	Oude Rijn	-	>1.5	>-1.5	-	-	Early medieval incision	Ua 36484	Early and Late medieval	Den Hartog, 2010a
R1	Oude Rijn	>10	3	-1	-	-	Late roman/Early medieval	GrA 43292	no finds	Hoegen, 2013
R2	Oude Rijn	20	2.5	-0.8	-	-	Late medieval	SUERC 27873; SUERC 27874	Late medieval	Hoegen, 2013
S	Vecht	-	-	-	-	-	Late medieval river movement?		Late medieval?	ABKU 1982: Oude Gracht 136
T	Vecht	-	>…..	>…..	-	-	Late medieval river movement	GrN 20345; GrN 20346; GrN 20945	Late medieval	ABKU 81: Jan Meijenstraat en Waterstraat; ABKU 1986 Jacobstraat; Van Moortel, 2009
U	Vecht	25	2.5	-2.5	-	-	Late medieval		Late medieval	Den Hartog 2009c
V	Vecht	13	~ -1 – 1.5	-0,4	-	-	Late medieval	UtC 14937	Late medieval	Unpublished
W	Vecht	~10	~ 1	-0.55	-	-	Late Roman/Early medieval	GrA 43211	no finds	Diependaal,2008; Den Hartog, 2013c
X	Vecht	~10	~ 1	-0,05	-	-	Late medieval	GrA 43293; GrA 43295	Late medieval	Den Hartog, 2013c

7 Synthesis

This thesis is aimed at assessing the impact of environmental change on human activity along the Oude Rijn in the Roman and part of the Medieval period (~AD 1-1122) in The Netherlands. The research questions were:

1. How did the landscape along the Oude Rijn look in detail in the Roman and Medieval periods?
2. Which landscape elements were used for settlement locations?
3. To what extent and how was the outline of the northwestern frontier of the Roman Empire – the *Limes* – determined by the natural landscape of the Rhine delta?
4. To what extent could the natural landscape of the Oude Rijn provide the local population and the Roman army with sufficient supply of wood and food?
5. How did the evolution of the Oude Rijn distributary effect occupation patterns?
6. What was the interrelationship between the landscape development and settlement change, and to what extent did the landscape and environmental change constrain human activities?

To this end, studies of fluvial archives were combined with archaeological, historical, and palaeobotanical research. This substantially improved the reconstruction of the timing and phasing of river landscape development, and the understanding of its influence on past human settling in the Rhine-Meuse delta, especially along the Lower Rhine in The Netherlands. This research yielded the following main results:

1. An integrated system of forts and watchtowers was erected in the western part of the Lower Rhine from the 40s AD onwards on the southern natural levees, directly along the river and regardless of height and composition of the subsoil. These structures were erected to guard all routes that provided natural access to the river and to protect the delta and this part of the Roman Empire from Germanic invasions (Chapter 2).
2. The bio-archaeological research overview indicates that the local population in the Lower Rhine Delta did produce a surplus of e.g. cereals and livestock to supply the Roman army. Most of the wood for the construction and repairs of the military constructions was acquired from the woodland in the surrounding area (Chapter 4).
3. Modelling of the demand and supply of the Roman Army along the Lower Rhine shows that the landscape in the Early Roman period (AD 40-70) posed no limit to satisfy the demand of the total population in the area for these products. However, the pressure on the landscape increased over time because of rising population numbers. From the end of the 1st century AD onwards, the landscape may have posed an upper limit on the availability of local resources and thereby on local production (Chapter 5).
4. The local population along the Oude and Kromme Rijn was probably much more involved than hitherto assumed in the provisioning of the Roman army in the Lower Rhine Delta between fort Vechten and the North Sea, especially regarding cereals (Chapter 5). However, local meat supply for the Roman army most probably remained problematic because the rural settlements would have to keep implausibly large cattle herds (Chapter 5).

5. Recent research in the Rhine-Meuse delta has revealed that young crevasse splay complexes were preferred locations for human settlement within flood basin areas. This implies that human occupation in the Rhine-Meuse delta was more extensive than previously thought (Chapter 3).
6. The avulsion of the Oude Rijn and Kromme Rijn occurred in distinct phases of channel morphodynamics over a 1000-yr period of river abandonment and three steps can be recognised in this development (Chapter 6): 1) a period of slowly decreasing river discharge and limited lateral channel movement, 2) a period in which the river carried very little water due to additional avulsions further upstream in the delta, and 3) the final silting-up phase causing shallowing and narrowing of the river channel, the formation of very sharp meanders, and a temporarily increase of flooding frequency.
7. The settlement history largely followed river activity, and people did not influence the avulsion process, although the settlement history was further directed by socio-economic and political factors. Only during the third phase of the Kromme Rijn avulsion (~AD 800-1122), the alluvial ridges were temporarily abandoned probably because of temporarily increased flooding frequencies (Chapter 6).

7.1 Geoarchaeology across scales

The preceding chapters are based on studies performed at scales that differ both in time and space, varying from individual excavations to research at delta scale (the Netherlands; Figs. 7.1, 7.2). Research objectives vary across scales, whilst different scale levels may require different methods to answer specific research questions.

7.1.1 Excavation and coring campaigns

An excavation is the smallest scale level of archaeological research, usually covering several tens of m^2 to a few hectares, and mostly is focused on time spans ranging from several decades to several centuries (Fig. 7.1). This kind of research is generally performed after non-destructive prospecting campaigns (e.g. desk research, coring campaigns, field surveys and/or geophysical research) have been executed. The main aim of geological research at this level is to reconstruct the local geological setting and palaeogeographical development. Studies at this local scale form the basic building blocks for further up-scaled reconstructions. Therefore, it is crucial during this phase to obtain formal, normalised lithological descriptions of the subsoil exposed in sections or in corings and interpreted in facies units (Fig. 7.3). The layers in sections at excavations are primarily identified in the field based on differences in colour and lithology, and they are sequentially numbered. In river delta areas, the further description of the facies includes texture, organic content, gravel content (visual), colour (subjective), carbonate content, iron content, groundwater and reduction level, sedimentological phenomena, compaction level, and the presence or absence of archaeological indicators (e.g. type, size, number). The interpretation in formal lithogenetical terms should be described separately to allow later re-interpretation.

Various techniques are deployed for age determination of lithological units, of which radiocarbon and OSL-dating, dendrochronological dating, and the presence of tephra layers are the most common. However, the time frame of the formation of the lithological units often already is more precisely constrained by archaeological dates derived from find layers or from accumulated waste in (some of) the units.

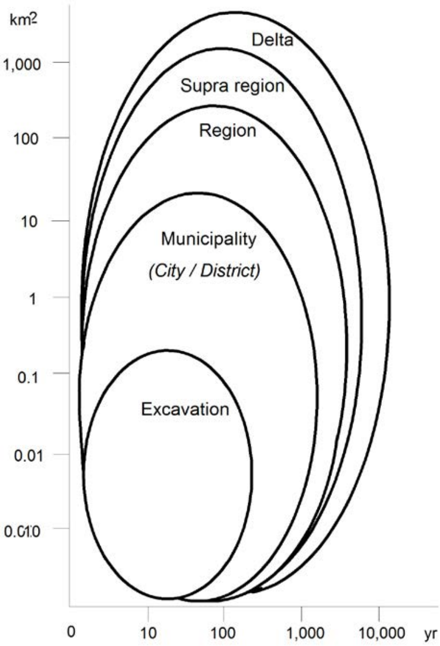

Figure 7.1 Various scale levels of geoarchaeological research in the Rhine-Meuse delta.

Samples for palaeo-ecological research that contribute to environmental reconstructions are taken from the section profiles. Macrofossils (e.g. fruits, seeds and other organic macro-remains), pollen, phytoliths, and wood in these samples provide proxy data for the reconstruction of local and/or regional vegetation, influence of human activities, food sources, and wood use. Molluscs, ostracods, fish remains, foraminifera, and diatoms provide information on the salinity of the water in the river channels, lakes or floodings, as well as on tidal influence.

Micro-morphological analysis of the soil material provides additional information about the formation processes of natural and human-caused lithological units. It may help to identify former land use of buried soil layers (e.g. tillage, trampling), and to distinguish various kinds of domestic and specialised activities (e.g. derived from anthropogenic pits and floors layers).

The abiotic landscape development at site level before, during and/or after the period of habitation and/or land use is reconstructed based on the combined description and interpretation of the lithological units, the results of the age determinations, and the outcome of the other palaeo-environmental analyses (Fig. 7.3). In this manner, it becomes clear whether the site for example

Table 7.1 Various scale levels of geoarchaeological research along Oude Rijn and Kromme Rijn listed per chapter.

	Excavation	Municipality	Region	Supra region	Delta
Chapter 2	X			X	
Chapter 3	X				X
Chapter 4	X			X	X
Chapter 5				X	
Chapter 6	X	X	X		

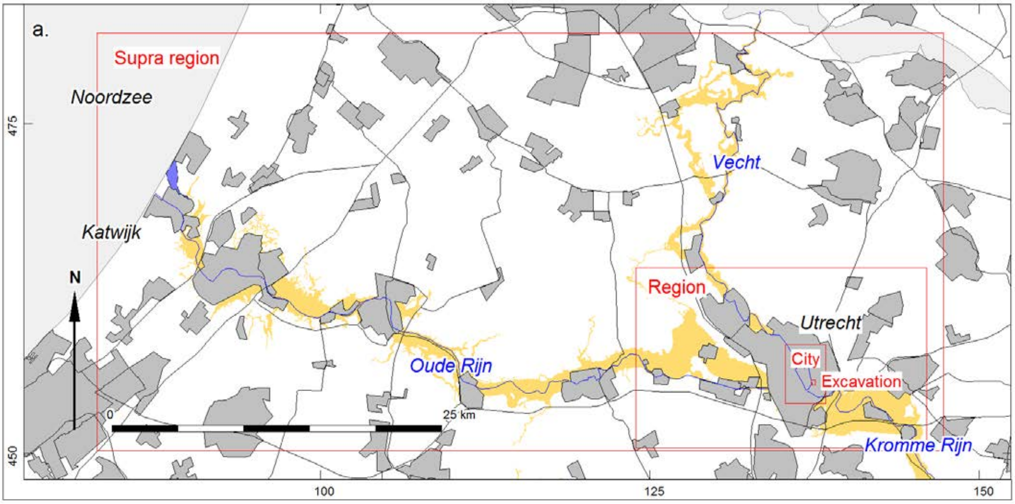

Figure 7.2 Various scale levels of geoarchaeological research along Oude Rijn and Kromme Rijn as applied in this thesis projected on the topographic map of the research area.

was situated on a levee or crevasse splay, and/or alongside a (residual) channel. Furthermore, the local history of fluvial morphodynamics is revealed, such as the local shifting of a river channel, the burying or (partial) erosion of the study site due to river flooding, or the in-filling history (material and duration) of a residual channel.

The documentation of the excavation research level provides the basic building blocks for all reconstructions presented in this thesis (Fig. 7.2b). The palaeogeographical reconstructions and archaeological settlement patterns presented in this thesis are based on a vast amount of excavations (Chapters 2-6). To make the reconstructions verifiable, the studies used in this thesis are listed per chapter, often in separate Appendices (Appendix B and D). The quality of the site descriptions and interpretations varies strongly per excavation or survey. Especially older studies often contain merely brief descriptions of the natural subsoil, such as 'sand' or 'clay', and occasionally subsoil descriptions are sometimes completely absent or only indicated in terms of 'natural soil'. Such lack of information seriously hampers later interpretation and the inter-site integration of information from individual sites.

Linking archaeological information to landscape and landscape dynamics requires re-interpretation of the lithological descriptions of each excavation into one of the following facies units: channel, levee, residual channel, flood basin, or crevasse splay deposits (Berendsen 1982; Törnqvist, 1993; Weerts, 1996). These are the basis for subsequent reconstruction of geomorphological units, such as meander belt, natural levee, flood basin, crevasse splay, residual river channel, or crevasse channel. Age determination of the morphological units is primarily based on ^{14}C and OSL dating, of which the reliability is assessed first. Furthermore, the archaeological artefacts may indicate the *terminus ante quem* age of the units on/in which they are found. Based on these interpretations, datings, and available paleo-environmental information, the local palaeogeography is reconstructed including its development through time and/or its influence on human occupation or land use. Following these

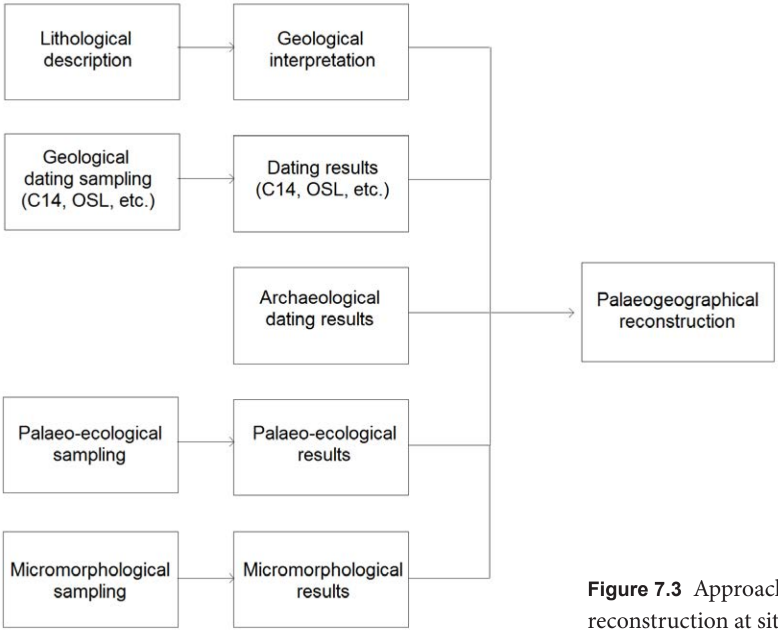

Figure 7.3 Approach for palaeogeographical reconstruction at site level.

steps in this study, it was possible to reconstruct the rebuilding of a Roman watchtower along the *Limes* in Leidsche Rijn, which followed the shifting of the river bend which it overlooked (Fig. 2.9), and the gradual sinking of crevasse splays in time due to subsidence and ongoing sedimentation in the surrounding flood basin, causing the abandonment of archaeological sites (Fig. 3.8).

7.1.2 Municipality

A municipality usually covers several km^2, often including a small part of one or several alluvial ridges, and has a (geo)archaeological time span ranging mostly from several centuries to over a millennium (Figs. 7.1, 7.2). Research at this scale generally aims to determine the distribution of alluvial ridge(s) versus flood basin(s) and possible crevasse splay complexes, as well as settlement distribution within the territory of the municipality. In the case of a city with largely overbuilt grounds, regional landscape development can be reconstructed by combining the geoarchaeological outcome of multiple excavations carried out within the city boundaries. In some cases, maps of the subsoil are available, produced prior to large-scale building activities that occurred in the second half of the 20th century (e.g. soil, geological, and geomorphological maps). In many cases, additional information about the subsoil can only be obtained from corings. Supplementary studies of old topographical maps can be deployed to locate curved road and ditch patterns possibly indicating the former presence of swales and residual channels. Sometimes, the development of a meander within the channel belt can be traced based on excavations that revealed the location, depth, and migration of the river channel. This approach was used in the reconstruction of the Oude Rijn meander courses near the city of the Utrecht described in Chapter 6 (see also 7.1.3).

Many municipalities also encompass a large surface of rural areas. Here, landscape development can often be reconstructed by combining the geological outcome of archaeological site excavations with existing regional geological maps. Such maps display large landscape features, such as the distribution of channel belts, levees, and crevasse splays. Geographical Information System (GIS) methods allow combining these maps with other existing maps (on e.g. soil or geomorphology), and further improving detail by using a high-resolution digital elevation model (DEM) of the present land surface based on laser altimetry (LIDAR). The Dutch LIDAR data cover the country completely and are freely available (Rijkswaterstaat-AGI, 2005). These data show micro-topographical differences in the youngest river deposits in high detail. Such height differences determined local flooding frequencies and ground water levels, and accordingly the suitability of the area for human activities. Furthermore, several geomorphological features are well identifiable on high-resolution elevation maps (Berendsen and Volleberg, 2007; De Boer *et al.,* 2008). Examples include residual channels, older and buried alluvial ridges, and crevasse splay complexes of which the elevation is slightly higher than the surrounding area due to differential consolidation of the covering clay and peat layers. Still, information about deeply-buried palaeo-landscapes can only be obtained through high-resolution coring campaigns and archaeological excavations. Both these approaches were adopted in the reconstruction of the Oude Rijn alluvial ridge and crevasse splay deposits in the Rhine-Meuse delta (Chapters 2, 3 and 6).

7.1.3 Region

A region stretches out across several municipalities, usually covers several hundreds of square kilometres, includes a considerable part of one or several alluvial ridges and has a (geo) archaeological time-span mostly ranging from several centuries to several millennia (Figs. 7.1, 7.2). Regional studies focus on reconstructing the relationship between the location of alluvial ridge(s) and settlement distribution patterns, sometimes through time within these municipalities. Regional landscape development is reconstructed using the same approach and methods as those used on municipality scale. In some cases, the chronological development of meanders within a channel belt can be reconstructed based on archaeological excavations revealing the location, depth, and migration of the river channel.

The combined results of a regional geological map and archaeological excavations on this level form the basis for establishing detailed palaeogeographical maps of the area through time. These maps may demonstrate whether the physical environment or changing landscape (e.g., the local height of the surface or the distance to a river) influenced the spatial distribution of settlements. If such patterns exist, the environmental conditions influencing site locations might become clear.

This approach was adopted in this thesis for the reconstruction of the Oude Rijn alluvial ridge and crevasse splay deposits in the wider spatial context of the Rhine-Meuse delta (Chapters 2, 3 and 6). The geoarchaeological information of the individual excavations along the Oude Rijn were subsequently up-scaled to city-district and region level through synthesis, LIDAR data, and information from existing maps which resulted in detailed regional landscape reconstructions (Chapters 2, 3 and 6). The position of the archaeological sites on these palaeogeographical maps revealed several cases of environmental factors that determined site locations. The palaeogeographical reconstruction in Chapter 2 shows that Roman military sites without exception were located directly along the river, irrespective of height and composition of subsoil, whereas Roman rural sites near Utrecht were all situated on the highest parts of the levees (Chapter 6, Fig. 6.8 and Appendix D – Fig. D6). The same pattern is visible in the distribution of Roman military and rural sites further downstream along the Oude Rijn (Fig. 2.4 and Appendix A). Here, rural settlements were also built on elevated crevasse splays of the Oude Rijn (Chapter 3). This shows that the physical environment, e.g. surface height, was an important location factor for rural settlements during this period. In contrast, settlement location does not seem to have been influenced by distance to the river. This changed over time, as Early Medieval settlements (c. AD 525-800) around Utrecht and further downstream without exception were situated on the highest natural levees directly along a river or a re-activated residual channel (Chapter 6.4.3, Fig. 6.8c). In this manner, the risk of flooding was minimised, while direct access to a navigable channel for exchange and trade was guaranteed. Furthermore, the settlement history and continuity of Utrecht and its surroundings were influenced by landscape development as well as by changing flooding frequency during the abandonment phase of the Oude Rijn. During the start of the final silting-up phase, increased flooding probably made agricultural activities very difficult and led to temporary abandonment of settlements (Chapter 6.5.4). In short, changes of the landscape often influenced human occupation and land use throughout the studied time interval, whereas humans hardly affected the river landscape directly. In the Oude Rijn area no evidence was found for large-scale building of dams or dikes until the 11-12th centuries AD.

7.1.4 Supra region and delta

A supra region includes an entire alluvial ridge, or even a complex of several alluvial ridges, usually covering several hundreds to a few thousands km^2, and considers a (geo)archaeological time-span often covering several millennia (Figs. 7.1, 7.2). Studies at this scale aim at reconstructing landscape development as well as the broader context of settlement patterns and connecting routes. The applied methods are essentially the same as those used at regional scale. Palaeogeographical reconstructions at this scale encompass the landscape in a much broader sense, addressing among others the presence and distribution of crevasse splays complexes, flood basins, and peat areas (e.g. fens versus bogs).

The Dutch Rhine-Meuse delta covers several thousand km^2 and its Late Glacial and Holocene development lasted c. 14,000 years (Fig. 7.2). The delta and its evolution have been reconstructed in high detail using a vast coring data set and LIDAR data, and thousands of ^{14}C-dates and archaeological finds (Cohen *et al.,* 2012). This dataset has enabled the production of uniquely detailed palaeogeographical maps for different time slices in the past, showing active river branches, recently abandoned rivers, and river courses that were long since abandoned. In this manner, these maps for these times show the distribution of alluvial ridges that potentially were available for human settlement.

Patterns in landscape development and their influence on settlement history can be derived by overlaying palaeogeographical maps with large-scale distributions of archaeological finds (https://archis.cultureelerfgoed.nl; see Fig. 1.3). Inferred patterns may reveal the larger-scale factors controlling site distribution, and the influence of a changing landscape on settlement patterns, or vice versa. They may demonstrate which alluvial ridges were suitable for settlement, and which were not suitable (anymore) because of their low-lying position or burial. Furthermore, these patterns may display how transport routes networks evolved, and demonstrate the effects of changing route networks on societies. In turn, this may provide information about the cultural impact of landscape change.

This large-scale approach was already adopted in previous reconstructions and has shown that the delta, which provided restricted conditions for settlement, nonetheless was continuously inhabited and offered good opportunities for groups of Mesolithic migrating hunter-gatherers (e.g. Louwe Kooijmans, 2001a; 2001b; 2007; Louwe Kooijmans *et al.,* 2005; Zijl *et al.,* 2011; Moree and Sier, 2015), and from the Neolithic onwards for subsistence farming (e.g. Henderikx, 1987; Willems, 1986; Arnoldussen, 2008; Jongste, 2008; Arnoldussen and Fokkens, 2008; Dijkstra, 2011). However, landscape development in the delta did influence settlement dynamics at delta scale as avulsions created new alluvial ridges, while abandoned ridges were covered with new sediments over time and became unusable (e.g. Groenhuizen and Verhagen, 2015; Pierik and Van Lanen, 2017; Van Lanen and Pierik, 2017). Spatial analyses show that settlements delta-wide progressively shifted towards higher areas between AD 250 and 750, on average by 20 cm over this period, which was coeval with an increased frequency of severe Rhine floods. The observed spatial differences demonstrate that this trend is most notable in the least-elevated areas. In areas where new large river branches developed, settlements shifted towards higher-elevated parts of the landscape or even became completely abandoned, probably because of more frequent and severe floods (Pierik and Van Lanen, 2017). Furthermore, these analyses show that large parts of the Rhine-Meuse delta route network system were persistently used during the Roman period and Early Middle Ages despite local settlement dynamics and changing natural settings (Van Lanen and Pierik, 2017).

This thesis demonstrates the further upscaling of geoarchaeological data into a larger framework of an entire alluvial ridge, in this case the 'supra region' Kromme Rijn – Oude Rijn. This resulted in palaeogeographical maps covering large areas, thereby revealing the environmental location factors of the Roman military structures. For example, there are strong indications that the location of the Roman forts along the Oude Rijn – the western part of the Dutch *Limes* – was determined by the distribution of waterways in this part of the delta, since these forts without exception were situated directly opposite or alongside waterways that provided natural access to the river Oude Rijn (Chapter 2). In addition, their location directly along the water side, irrespective of the height of the levee and composition of the subsoil, demonstrates the importance of good transport conditions. This factor apparently prevailed over living comfort, a quality much more readily provided on adjacent higher and drier natural levees further away from the river. In contrast to what was previously thought, the size of the forts on the other hand was not limited by the landscape, since the areas where they were built could accommodate much larger forts (Chapter 2).

Landscape reconstructions through time also support reconstructing and understanding the impact of environmental change on habitation patterns. The role of the formation, size, thickness and sedimentological sequence of crevasse deposits and subsoil as controls of the feasibility for occupation or other human use is demonstrated in Chapter 3. Here it is shown that young crevasse splay complexes were preferred locations for human settlement within flood basin areas. This implies that human occupation in the Rhine-Meuse delta was more extensive than previously thought. Farmsteads were built on splays that varied in size (from barely exceeding the size of one farm stead to several km^2) and morphology (e.g. lobed or elongated). During the period of occupation, the crevasse splays gradually lost their relatively high position in the landscape due to subsidence and ongoing sedimentation on the flood basin. Some locations were abandoned after a few decades, while others remained occupied during a much longer period depending on the relative subsidence rate of the land. Likewise, the Kromme Rijn – Oude Rijn abandonment described in Chapter 6 influenced occupation patterns and land reclamation in Late Roman and Medieval times.

The various landscape units in the delta form areas of potential land use (e.g. arable land, life stock breeding, wood production, fishery, hunting-gathering). By quatification of the surface of these units, palaeogeographical maps form a template for models of 2D palaeo-ecological patterns, or quantitative estimates of carrying capacity of the landscape to supply the food and raw-material demand of the local population. Chapters 4 and 5 demonstrate this for the Lower Rhine alluvial belt as landscape template for food and material provision for the Roman army and local population. The large-scale palaeogeographical reconstruction of the Kromme Rijn – Oude Rijn area shows what the landscape along the *Limes* looked like, not just the alluvial ridge, but also in a wider sense including the distribution of associated crevasse splays complexes, the size and distribution of the flood basins, and the nature of the adjacent peat areas (e.g. eutrophic fen woodlands, mesotrophic reeds swamps, or oligotrophic peat domes; Chapter 2). Each geomorphological unit had distinct characteristics in terms of elevation and composition of the subsoil (Fig. 4.3), which determined the suitability of the area for settlement, woodland, agrarian use, and animal husbandry (Table 5.1). Thereby, this distribution defines the potential land use of the area and thus the carrying capacity of the landscape (Chapter 4).

7.2 Living along the *Limes*

Since the preservation conditions of organic material in the Dutch Rhine-Meuse delta is exceptionally good due to the high water levels in this wetland area, it was possible to make a qualitative synthesis of the use of the landscape in Roman times and to answer primary questions to assess the provisioning potential of the landscape for its human population (Chapter 4): a) which cereals were grown and consumed by the various groups in the area (Roman army, *vicani,* and local farmers), b) which animals were kept, bred and eaten by these groups, c) which wood species were used for which construction purposes, and d) what type of food was derived from elsewhere (Chapter 4).

The palaeogeographical maps served as a template for assessing the provisioning potential in chapters 4 and 5, by quantifying the surface areas of geomorphological units, and linking these to vegetation cover, wood type, and suitability for grazing and cultivating crops. The demand-supply modelling shows that the landscape in the Early Roman period (AD 40-70) posed no limit to satisfy the wood and food demand of the total population in the area. However, pressure on the landscape increased over time because of a rising population. From the end of the 1st century AD onwards, the landscape may have posed an upper limit on the availability of local resources and, thereby, on the local production (Chapter 4). Furthermore, the local population along the Oude Rijn and Kromme Rijn probably was much more involved in the provisioning of the Roman army in the Lower Rhine Delta between fort Vechten and the North Sea, especially regarding cereals, than hitherto assumed (Chapter 4). However, local meat supply for the Roman army most probably did form a problem (Chapter 4).

In contrast to measurable geological characteristics, the uncertainty of archaeological variables (e.g. population size, vegetable-animal energy requirement ratio, rotation system, yields, etc.) is inevitably large, since the magnitude of these figures can only be estimated, interpreted, or hypothesized. Therefore, archaeological computational modelling and sensivity analysis to reveal parameter utility and impact should be used differently (Brouwer Burg *et al.,* 2016). Nevertheless, our assessments provide a first estimate of the magnitude of the demand from and the supply to the Roman army in a supra region thus far (Chapter 5). The ecological artefacts and archaeological finds in the area support the results of the model (Chapter 4). Similar research has only been conducted for Neolithic pile dwellings in South-West Germany (e.g. Gross *et al.,* 1990; Maier, 1999; Jacomet, 2009; Ebersbach, 2013; Baum, 2014; 2016).

Next steps in modelling or Agent Based Modelling (ABM) should be based on conceptual models that are supported by comprehensive databases like those used in this thesis. Meanwhile, this model has already been used for further modelling (simulation modelling: De Kleijne et al., 2016; Van Lanen *et al.,* submitted; Verhagen *et al.,* 2016; ABM: Groenhuizen and Verhagen, 2015, 2016;

Joyce and Verhagen, 2016; Joyce, in press). These new studies support the conclusions of this thesis and, moreover, add further detail. Likewise, ABM modelling of late Neolithic crop cultivation in the Alpine forelands was used to test existing hypotheses about the reasons for settlement relocation, resulting in arguably better explanations for the observed patterns (Baum 2014a; 2014b; Baum *et al.,* 2016; Jacomet *et al.,* 2016).

7.3 Early water management

First habitation in the delta mainly adapted to changes in the river network and flooding frequency (e.g. Cohen *et al.,* 2016). The first attempts of water management in the Rhine-Meuse delta date to the Late Iron Age (250-12 BC), and occurred in the tidally-influenced Maas estuary near Rotterdam (Fig. 2.1, *Helinium*) where several dams and culverts were excavated that served to prevent (salt) water to intrude into the flood basins (Ter Brugge, 2002). Water control was eventually institutionalized during the Roman Empire (Svetonio, *Augustus* 37). Evidence of water management in the Netherlands is present in the form of historical annals mentioning a) the *Fossa Drusiana*, a Roman canal constructed under the command of Drusus (12 BC) to connect the Rhine with the Frisian coast (Tacitus, *Annales* II, 8 and Suetonius, *Vita divi Claudii* 1.2), b) the *Moles Drusi*, a dam built to redirect the water flow into the most northerly Rhine branch (Nederrijn; Tacitus' *Historiae* V,19 and Tacitus, *Annales* XIII, 53), and c) the *Fossa Corbulonis,* a canal to connect the Rhine to the Meuse and to avoid the dangerous North Sea in c. 50 AD (Tacitus, *Annales* XI, 18-20 and Cassius Dio, *Historia Romana* LXI 30: 4-6). However, no archaeological evidence of the *Fossa Drusiana* and *Moles Drusi* has been found yet, probably due to medieval river erosion (Chapter 2; Verhagen *et al.,* 2017). However, the remains of Corbulo canal have been uncovered (e.g. De Kort and Raczynski-Henk, 2008; 2014; Chapter 2). Furthermore, a canal was probably dug near Utrecht, but due to the subsequent water flow and resulting erosion it is hard to prove that this canal was initially dug by man (Van Dockum, 1997). By digging a relatively short canal through the watersheds these canals linked existing channels, creating safer and shorter inland water routes with minimal effort (Chapter 2). The construction of culverts near Rotterdam continued into the Roman period (Ter Brugge, 2002). Recent archaeological evidence shows that the Meuse estuary also may have been connected to the Scheldt estuary in the south through a similar combination of natural inlets connected by a dug canal (Van der Kroft *et al*., 2006; De Bruin *et al*., 2012; Jansma *et al*., 2014b). However, no archaeological evidence has been found of Roman dams, dikes, and drainage of wetlands in the Rhine-Meuse delta.

7.4 Recommendations for future research

This study shows that an interdisciplinary approach adds to our knowledge of habitation patterns in a dynamic delta landscape in (pre)history. The historical paradigms of either prioritizing environmental influence (in the past referred to as 'environmental determinism') or socio-cultural controls on habitation history are not mutually exclusive. Both the given environment and human settlement in this environment must have had effects, which often occurred simultaneously. It can no longer be denied that in dynamic and unembanked wetlands such as the Rhine-Meuse delta the environment did have a pronounced effect on the manner in which humans adapted to, and interacted with, their surroundings. Here, river activity acted on various scales, varying from yearly floodings causing fluctuating (ground-) water levels to long-term avulsions, and erosion and deposition processes which changed the local, regional, and delta geomorphology. This activity influenced both the possibility for human activities and resources, such as settlement patterns, agriculture, husbandry, fishery, transport and river-based transport, and the possibilities of water management and other adaptations of the landscape. Furthermore, it determined the potential preservation of archaeological sites and material by erosion, burial, deterioration and oxidation, and thereby might create a misleading spatial distribution and a taphonomic bias. The likely influence of these latter effects should first be determined or excluded before socio-cultural and economic factors are assigned as underlying changes observed in the archaeological record.

This thesis shows that a detailed landscape reconstruction is crucial for interpreting changes in settlement development and land use in dynamic landscapes such as past lowland delta areas. Here, the landscape and its changes influenced the possibilities for habitation, land use, and transport routes. From the data presented in this thesis it appears that flooding, migration, and avulsions of the rivers in the Rhine-Meuse delta were taken for granted until c. the 10-11th centuries AD. Until then, habitation in the delta responded to changes in the river network and flooding frequencies as well as to the socio-cultural, economic, and political situation. From c. the 12th century onwards the rivers were 'tamed' on a large scale using dikes and dams.

In order to produce detailed palaeogeographical reconstructions such as those presented in this thesis, the geological information from the basic building blocks (i.e. excavations) is crucial. The strong competition in commercial archaeology in the Netherlands nowadays results in cost-saving measures, for example by entrusting the description of the natural subsoil to Field Archaeologists instead of Quarternary Geologists. This approach often results in poor quality, non-standardised soil descriptions and the omission of geological units and/or sedimentological structures, leading to erroneous interpretations which cannot be re-interpreted. Furthermore, the influence of the subsoil and geological history on (the preservation of) the archaeological site nowadays often remains unclarified. It is, therefore, important that Archaeologists and Quaternary Geologists collaborate in such research. Geologists often profit from the exact, well-confined dates of archaeological material, which aids them in reconstructions of e.g. the velocities of river bend migration, sedimentation velocities, and the time span of soil formation. Archaeologists in turn profit from such collaborations because of the increased understanding of the geo(morpho)logical context in which social development occurred and, through the incorporation of palaeo-ecological reconstructions, of the economic and cultural background of the studied sites. To enhance interaction between these domains, the original data should be easily available, preferably through the internet. It would be ideal if every municipality added a well-argued procedure to this end into its archaeological policy agenda as part of the legal duty of care of archaeological heritage.

At present, the general low-density character of data obtained in other deltas throughout the world – both geomorphological and archaeological – inhibits the creation of similar detailed palaeogeographical reconstructions for these deltas. This prevents determining which environmental conditions in general influenced human occupation patterns through time in wetland areas and whether the location factors as identified in the Rhine-Meuse delta are universally valid or not. A general validity seems likely, since present, local palaeogeographical reconstructions in the Mediterranean deltas show a similar influence of the presence of alluvial ridges on settlement locations and on the preference of settlement on higher levees (Chapter 6). Future research in these deltas may provide more data and subsequently improve our insight in the influence on, and interaction between, landscape development and habitation history. As a starting point this would require high-quality observations per site, which should be placed in a local environmental context including details regarding the exact alluvial ridge where the site was located, the height of the levee, the distance to the flood basin, the nearby presence of a (residual) channel, *et cetera*. By up-scaling these reconstructions, this approach finally may provide a conclusive answer to the question to what extent the environment and environmental change in deltas worldwide influenced occupation patterns and the history of their early settlers, as recorded in archaeological remains through time.

Summary

River environments have played a vital role in human history. Alluvial landscapes comprise ecologically rich and varied environments and thereby provide attractive environments for humans. River deltas are therefore long since inhabited. However, the intensive exploitation of rivers and deltas has increasingly caused problems, particularly in lowland deltas. Solving the current problems also requires a more fundamental understanding of how natural and societal systems interact. Such interactions already occurred during first occupation of these deltas: the earliest settlers already had to deal with the natural changes and delta dynamics, such as river flooding and changes of the river courses. This raises the question how these societies responded or adapted to, or prevented changes and dynamics, of these wetland areas. Answering this question would be a first and important step in the further understanding of the interaction between social and natural systems in deltas.

The Rhine-Meuse delta in the Netherlands is one of the presently densely-populated and heavily-engineered deltas with a long settlement history in which the Roman Period has a special position regarding the relation between the social and natural systems. Alluvial landscapes have been the subject of worldwide geoarchaeological research. In spite of the growing number of studies employing archaeological evidence, radiocarbon and OSL dating, modern surveying techniques, and GIS methods to reconstruct Holocene river histories, there have been few attempts worldwide to synthesise these data at delta scale. The wealth of geological and archaeological data in the Netherlands, the publicly-available databases, and excellent preservation conditions constitute a perfect case to provide detailed palaeogeographical reconstructions of a complete distributary, the Oude Rijn, and to decipher the effect of the landscape and its dynamics on settlement locations in the delta in various time periods on a larger scale. This study aims to enhance the generic understanding of past river environments and their influence on human settlement and land use. The main objective is to assess the impact of environmental change on human activity along the Oude Rijn in the Roman and Medieval periods (~AD 1-1122).

To this end, a two-step approach was deployed. During step 1, a landscape analysis was conducted for the Oude Rijn area using a Geographical Information System (GIS). By combining various maps with geoscientific information with coring data, (older) topographical maps, LIDAR data, and (geo)archaeological research site-scale data, detailed palaeogeographical maps were reconstructed. Step 2 entailed the overlaying of the archaeological site distributions on these palaeogeographical maps. This enabled identifying spatial relationships between settlement location/land use and geomorphological unit(s). Furthermore, it was analysed whether changes in settlement locations coincided with landscape changes, and thus might be triggered by landscape development through time.

From the AD 40s onwards a dense military system was established along the Oude Rijn in the Netherlands (Chapter 2). Long since, it has been questioned why this system was established in a wetland area and even was turned into the northwest frontier of the Roman Empire, the *Limes*. A new and highly-detailed palaeogeographical map was constructed. This reconstruction provides insight in, and understanding of, the interactions between both the natural environment in this part of the delta and the establishment of this part of the *Limes* along the Oude Rijn between Utrecht and Katwijk. This study shows that the distinctive landscape of the western Rhine-Meuse delta, with an exceptionally large number of tributaries, determined the spatial pattern of the military structures. All forts (*castella*) were erected on the southern natural levees of the river Rhine directly alongside

the river, regardless of the height and composition of the subsoil, and alongside or opposite routes that provided natural access to the river. We conclude that the aim was to guard all waterways that gave access to the river Rhine from the Germanic residential areas further north and from/ to the Meuse tributary further south in the delta. In addition, a system of small military structures, mostly watchtowers, was erected between the forts to watch over the river Rhine and its traffic. Furthermore, at least two canals were established to create shorter and safely-navigable transport routes to the river Meuse. At first, this integrated system of forts and watchtowers was probably built with the aim to protect against Germanic raiding and to create a safe corridor for transport and build-up of army supplies in relation to the British invasion in AD 43. Only later on, probably by the end of the 1st century, this corridor turned into a frontier zone.

As a next step, the formation and landscape development of crevasse splays was analysed to increase the understanding of the attractiveness of these often short-lived landscape features for settlement and human use in general (Chapter 3). Until recently, archaeologists in general assumed that human occupation of the Dutch river area in the Neolithic period and Bronze Age was rare and predominantly seasonal. Settlement and land use were thought to be limited to abandoned alluvial ridges and aeolian dunes. However, recent archaeological research has shown that Neolithic and Bronze-Age human activity occurred on many locations in the Rhine-Meuse Delta. Human settlement and agricultural land use in this delta dates from at least 3200 BC onwards and was much more common than previously thought. Crevasse splay complexes of active and abandoned river systems have been proven to have provided favourable sites for settlements. These elevated areas were suitable for agriculture as they were fertile, easy to plough, and were characterized by suitable hydrological conditions. In addition, people could exploit the surrounding floodplain for hunting, fishing, or herding their cattle. Furthermore, the river or residual river channel was available nearby for transport. From the start of the Middle Bronze Age stage B (1400 BC), occupation of crevasse splay deposits in the delta was widespread. Farmsteads were built on splays that varied in size and morphology. Some locations were abandoned after a few decades, while others remained occupied during a much longer time interval. During the period of occupation, the crevasse splays gradually lost their relatively high position in the landscape due to subsidence and ongoing sedimentation in the floodplain. LIDAR data combined with digital coring databases and/or detailed soil maps have proven to be an excellent method for the identification and mapping of crevasse splays and the archaeological sites these contain. The resulting new maps provide a major foundation for future archaeological prospection and preservation policy.

Chapter 4 contains an extensive review of the available data regarding agrarian settlements and focuses on the extent on which the landscape of the Oude Rijn provided sufficient sources to supply the local inhabitants and Roman army with building material, fuel, and food. Traditionally, historical sources and the marginal landscape in this region have led to the assumption that the Roman army in the Rhine delta was mainly supplied with products transported over medium and long distances. In a diptych of articles, we investigated whether this assumption is tenable for wood and food, based on archaeological, palaeo-environmental and geological research carried out over the past twenty years. The first article (Chapter 4) provides a review of the data, which leads to the argument that the Roman army procured wood and food (especially cereals and beef) from agrarian settlements in the immediate surroundings. The second article (Chapter 5) investigates the scale of local provisioning based on a new calculation model.

Analysis of wood data has demonstrated that wood for the construction of the forts, and also for later building activities, was acquired from the woodland in the *Limes*-zone. Most of the wood used in the construction of the forts around AD 40 came from the woodland on the levees and alluvial ridges. From the second half of the 1st century onward, most of the wood was derived from wetland woodland in the flood basins and the fen woodlands, where production woodland was probably located from the late 1st century onwards. Bio-archaeological research has provided indications for the surplus production of cereals and the breeding of livestock. The fields for cereals would have been located on the levees of the Rhine, older alluvial ridges, and dune ridges. Although the potential area for arable fields is limited, the requirements for wood and cereals do not appear to have been in conflict, because different parts of the landscape were used to obtain these products. Several landscape units could have been used for livestock. The required space for animal husbandry could therefore have conflicted with the spatial demands of arable farming and forestry. But it is precisely because livestock was not tied to particular types of landscape that the animals could have been grazed in places not used for the production of these other two space-consuming commodities, such as in the flood basins and the salt marshes. Grazing cattle in these latter areas certainly would not have been a second-best option, since due to regular flooding the growth rate of vegetation (i.e. food for livestock) in the flood basins was higher than average.

We also modelled and quantified the carrying capacity of the landscape and the demand and supply of the Roman army in the western Lower Rhine Delta regarding wood and food for the period AD 40-140 (Chapter 5). The absolute volumes of wood and food were calculated in m^3 and kCal, and converted into surfaces needed (in km^2). In addition, the acreage of available land in the area was quantified. A comparison of the demand and supply estimates reveals that the carrying capacity of the landscape was larger than hitherto assumed. Initially, the landscape was not limiting for the total demand. However, the pressure on the landscape increased due to a growing population, and upper limits of the possibilities of production defined by the landscape may have been reached in the 2nd century AD. Furthermore, our calculations show that wood and food, especially cereals, could be procured from agrarian settlements in the immediate surroundings. Therefore, the local population was probably much more involved in the provisioning of the Roman army in the Lower Rhine Delta than previously assumed. It seems likely that the Roman army combined local provisioning with extra-regional supply and long-distance transport.

In Chapter 6 we integrated geological and archaeological datasets to demonstrate the concurrence of the gradual abandonment of a major Rhine channel (Utrecht, The Netherlands), the development of human habitation in the area, and the interactions between them. The Utrecht case study highlights the stage-wise abandonment of a natural river channel, due to avulsion, coincident with intensifying human occupation in Roman and Early Medieval times (1st millennium AD). The analyses make maximum use of very rich data sets available for the study area and the tight age control that the geoarchaeological dataset facilitates, offering extra means of time-control to document the pacing of the abandonment process. This allowed us to quantify change in river dimensions and meander style and to provide discharge estimates for successive stages of the abandonment phase over a 1,000-year period of abandonment succession, from mature river to eventual Late Medieval overbuilt canal when the Rhine branch had lost even more discharge.

Continued geomorphic development during this period, which includes the 'Dark Ages' (AD 450-1000), appears to have been crucial in the development of Utrecht from a Roman army fortr to a Medieval ecclesial centre. The settlement dynamics in and around the city of Utrecht changed during the various phases of abandonment. In the bifurcating network of river branches forming the Rhine-Meuse delta, the main Rhine branch hosted the Roman *Limes* military border and transport route. The Rhine-Vecht bifurcation at Utrecht provided an excellent location to raise a Roman fort. Continued geomorphic activity during abandonment in Early Medieval times was characterised by enhanced overbank sedimentation and shifts in the position of bifurcations. River flooding became more incidental in this stage, and alluvial-ridge occupation became sensitive to flooding events for several centuries. We conclude this chapter by demonstrating that similar human-river interactions during Roman times occurred in several other deltas within the former Roman Empire, with differences depending on the position of a settlement within the delta, the overall hydrological situation, and the ability of societies to control the changing environment.

The combined study of fluvial archives and archaeological, historical, and palaeo-botanical data for the Rhine-Meuse delta substantially has improved the reconstruction of the timing and phasing of river landscape development, and the understanding of its influence on past human settling, especially along the Lower Rhine in The Netherlands in the Roman and Medieval periods (~AD 1-1122). Detailed landscape reconstructions are crucial for interpreting past changes in settlement development and land use in dynamic landscapes such as lowland delta areas. Without a detailed understanding of the river and landscape evolution of an area, past settlement history of this region cannot be interpreted correctly and must be handled with care.

Samenvatting

Riviervlaktes en delta's hebben een cruciale rol gespeeld in de menselijke geschiedenis. Ze bieden een ecologisch rijk en gevarieerd landschap en vormen daarmee een aantrekkelijke woonomgeving voor mensen. De intensieve exploitatie van rivieren en delta's heeft echter tot problemen geleid, zoals onder meer met de grondwaterstand, waterkwaliteit en overstromingsrisico's, vooral in laaglanddelta's. Het oplossen van deze problemen in de huidige tijd vraagt om meer fundamenteel inzicht in de wisselwerking tussen natuurlijke landschappen en samenlevingen. Deze interacties vonden al plaats tijdens de eerste bewoning van rivierdelta's. De vroegste bewoners moesten leren omgaan met veranderingen van de natuurlijke omgeving en de dynamiek in delta's, zoals overstromingen en het verleggen van rivierlopen. Dit roept de vraag op hoe deze samenlevingen reageerden op veranderingen en landschapsdynamiek van deze waterrijke gebieden; in hoeverre pasten zij zich aan of probeerden zij deze tegen te gaan? Het antwoord op deze vragen zou een belangrijke stap zijn in het beter begrijpen van de wisselwerking tussen natuurlijke en sociale systemen in delta's.

De Rijn-Maas delta in Nederland is een van de delta's die zeer dicht is bewoond. Deze delta is geheel bedijkt en kent een lange bewoningsgeschiedenis waarin de Romeinse tijd een speciale positie inneemt in de interactie tussen het maatschappelijke en het natuurlijke systeem. Rivierlandschappen zijn het onderwerp van wereldwijd geoarcheologisch onderzoek. Maar ondanks het toenemend aantal onderzoeken die de Holocene riviergeschiedenis proberen te reconstrueren op basis van archeologische gegevens, dateringen (^{14}C en OSL), moderne prospectietechnieken en GIS-methoden, zijn wereldwijd slechts enkele pogingen gedaan om deze gegevens te synthetiseren op schaal van een delta. De enorme hoeveelheid geologische en archeologische data in Nederland, de publieke toegankelijkheid daarvan en de buitengewone conserveringscondities bieden een ideale mogelijkheid om de gedetailleerde paleogeografische reconstructie te maken van een hele rivierloop. Daarnaast kan de invloed het landschap en haar dynamiek op bewoningslocaties in de delta in verschillende tijdsperioden op grotere schaal worden bestudeerd. Dit proefschrift probeert het algemene begrip van rivierlandschappen en hun invloed op menselijke bewoning en landgebruik in de periode voor de bedijkingen te vergroten. Het belangrijkste doel daarbij is het achterhalen van de impact van landschappelijke veranderingen op menselijke activiteit aan de Oude Rijn in de Romeinse Tijd en Vroege Middeleeuwen (ca. 1-1100 na Chr.).

In dit onderzoek is steeds een twee-stappen benadering gebruikt. Tijdens stap 1 is een landschapsanalyse uitgevoerd van het Oude Rijn gebied waarbij gebruik is gemaakt van een Geografisch Informatie System (GIS). Gedetailleerde paleogeografische kaarten zijn gemaakt door diverse bestaande geologische, geomorfologische en bodemkaarten te combineren met geowetenschappelijke informatie uit boringen, (oudere) topografische kaarten, hoogtegegevens (AHN) en (geo)archeologische onderzoeken. Tijdens stap 2 zijn de archeologische vindplaatsen op deze kaarten geprojecteerd, waardoor het mogelijk werd ruimtelijke analyses uit te voeren tussen bewoningslocatie/landgebruik en de geomorfologische eenheden. Daarnaast is gekeken of veranderingen in het bewoningspatroon samenvielen met veranderingen in het landschap en dus mogelijk de oorzaak of gevolg kunnen zijn geweest van de landschapsdynamiek die in de loop van de tijd plaats vond.

Vanaf 40 n. Chr. is een reeks van Romeinse forten aangelegd op de zuidoever van de Oude Rijn (Hfst. 2). Lange tijd heeft men zich afgevraagd waarom dit systeem hier, in zo'n waterrijk gebied, werd aangelegd en waarom het uiteindelijk zelfs de noordwestgrens van het Romeinse Rijk is gaan vormen, ook wel aangeduid als *Limes*. Een nieuwe, gedetailleerde paleogeografische kaart van de Oude Rijn en omstreken is gemaakt. Hiermee is inzicht en begrip verkregen in de wisselwerking tussen de natuurlijke omgeving in dit deel van de Rijn-Maas delta en de aanleg van de *Limes* langs de Oude Rijn tussen Utrecht en de monding bij Katwijk aan Zee. Dit onderzoek toont aan dat het specifieke landschap in dit deel van de delta met een groot aantal zijstromen vanuit de veengebieden de ruimtelijke verspreiding van de militaire structuren bepaalde. Alle Romeinse forten zijn op de zuidoever van de Oude Rijn gebouwd, direct aan de waterkant, ongeacht de hoogteligging of samenstelling van de ondergrond en altijd recht tegenover of grenzend aan doorgaande waterlopen die op de Oude Rijn uitkwamen. Daaruit wordt geconcludeerd dat alle bevaarbare zijriviertjes, die toegang gaven op de Oude Rijn, werden bewaakt. Dit gold zowel voor zijriviertjes vanuit de gebieden die door de Germanen werden bewoond, ten noorden de Oude Rijn, of die vanuit het zuiden vanaf de Maas. Daarnaast is, tussen de forten in, een systeem van kleinere militaire structuren (vooral wachttorens) opgericht, om toe te zien op de rest van de rivier en het bootverkeer. Verder zijn minstens twee kanalen aangelegd om kortere en veiligere vaarroutes te creëren van en naar de Maas. Dit integrale systeem van forten en wachttorens is waarschijnlijk in eerste instantie gebouwd ter bescherming tegen Germaanse invallen, en om van een veilige transport-route te creëren voor de aanvoer van troepen en materiaal ten behoeve van de inval van Groot-Brittannië in 43 n. Chr.. Pas later, vermoedelijk aan het eind van de eerste eeuw n. Chr., werd deze corridor omgevormd tot noordgrens van het Romeinse Rijk (de *Limes)*.

Een volgende stap was het analyseren van de vorming en ontwikkeling van crevasseruggen (hoge rug gevormd na oeverwaldoorbraak) om een beter begrip te verkrijgen van de aantrekkingskracht van deze relatief kortstondig aanwezige landschapselementen voor bewoning en landgebruik in het rivierengebied (Hfst. 3). Tot voor kort werd aangenomen dat de bewoning van de Nederlandse rivierdelta in het Neolithicum (5300-2000 v. Chr.) en de Bronstrijd (2000-800 v. Chr.) slechts op enkele plekken voorkwam en met name seizoensgebonden was. Men veronderstelde dat bewoning en landgebruik beperkt waren tot de oevers van verlaten rivierarmen en rivierduinen. Recent onderzoek heeft echter aangetoond dat Neolithische en Bronstijdbewoning op veel plaatsen in de Rijn-Maasdelta voorkwam. Bewoning en landbouwactiviteiten in de delta waren in elk geval vanaf 3200 v. Chr. veel algemener dan tot nu toe gedacht. Het blijkt dat crevasseruggen van zowel actieve als verlaten rivierarmen goede bewoningsmogelijkheden boden. Deze relatief hooggelegen locaties waren ook ideaal voor landbouw omdat de ondergrond vruchtbaar, gemakkelijk te ploegen was en geschikte hydrologische condities bezat. Het omringende komgebied kon worden gebruikt voor jacht, visvangst en het weiden van vee. Verder was de rivier of restgeul beschikbaar voor transport over kortere of langere afstand. Vanaf het begin van de Midden Bronstijd (vanaf 1400 v. Chr.) kwam bewoning in de delta op grote schaal voor. Boerderijen werden gebouwd op crevasseruggen, die sterk in vorm en grootte verschilden. Sommige locaties werden al na een paar decennia verlaten, maar andere bleven veel langere tijd bewoond, tot wel meer dan duizend jaar. Gedurende de bewoningsperiode verloren de crevasseruggen geleidelijk hun relatief hooggelegen positie in het landschap als gevolg van zakking van de ondergrond en verdergaande sedimentatie in het omringende komgebied. Het combineren van recente hoogtegegevens (AHN) met digitale boordatabases en/of gedetailleerde bodemkaarten blijkt een uitstekende methode om crevasseruggen en mogelijk archeologische vindplaatsen erop te lokaliseren en te karteren. De resulterende kaarten bieden een goede basis voor toekomstig prospectief archeologisch onderzoek en behoudsbeleid.

Hoofdstuk 4 en 5 bevatten een uitgebreid overzicht van de beschikbare gegevens over agrarische nederzettingen in de Rijn-Maas delta in de Romeinse Tijd en richt zich op de mogelijkheden die het landschap rond de Oude Rijn bood om zowel de lokale inwoners als het Romeinse leger in het gebied te voorzien van bouwmaterialen, brandstof en voedsel. Op basis van de historische bronnen en het marginaal geachte voorzieningsmogelijkheden van het landschap in dit gebied werd tot nu toe aangenomen dat het Romeinse leger in de delta werd voorzien van producten die over lange afstand werden geïmporteerd. Wij onderzochten of deze aanname geldig is voor hout en voedsel aan de hand van archeologisch, paleo-ecologisch en geologisch onderzoek, dat de laatste decennia is uitgevoerd. In hoofdstuk 4 wordt een overzicht gegeven van de beschikbare data. Op basis hiervan wordt geconcludeerd dat het Romeinse leger in de Nederlandse delta hout en voedsel (met name graan en vlees) verkreeg vanuit de agrarische nederzettingen in de directe omgeving. In hoofdstuk 5 wordt aan de hand een nieuw rekenmodel onderzocht in hoeverre het lokale landschap kon voorzien in de vraag naar materialen en voedsel.

De analyse van houtresten heeft aangetoond dat het constructiehout voor de bouw van de forten, en ook dat van latere reparaties en bouwfasen, afkomstig was uit de lokale bossen in de *Limes*-zone (Hfst. 4). Het meeste bouwhout uit de eerste bouwfase in de 40er jaren na Chr. kwam van bossen op de oevers van de Oude Rijn. In het tweede deel van die eeuw wordt het bouwhout vooral uit de bossen in de naastgelegen komgebieden en achterliggende broekbossen gehaald. Vanaf het einde van de eerste eeuw werd hier zelfs ook productiebos aangelegd. Het bio-archeologische onderzoek heeft aangetoond dat overproductie van granen en vee waarschijnlijk was. De graanvelden werden vermoedelijk aangelegd op oevers van de Oude Rijn, oudere stroomruggen en in de kustduinen. Hoewel de potentiele oppervlakte voor bouwland beperkt was, lijken de verbouw van hout en granen elkaar niet uit te sluiten, omdat ze in verschillende delen van het landschap konden worden geproduceerd. Voor het weiden van het vee konden verschillende landschappelijke eenheden worden gebruikt. Daarmee zou een conflict in landgebruik hebben kunnen optreden tussen het weiden van vee enerzijds en het verbouwen van graan en bosbouw anderzijds. Echter, door het feit dat het vee op veel verschillende landschapseenheden kon worden geweid, konden de dieren daar worden geweid waar de andere twee grote landgebruiksvormen niet mogelijk waren, zoals op de overige delen van de komgebieden en de kwelders in de kustzone. Dit was niet eens een tweede-keus optie, omdat de vegetatie (dus het voedsel) regelmatig overstroomde met voedselrijk water en daardoor een hoger producties opleverde.

Ook is de draagkracht van het landschap plus de vraag van de het Romeinse leger gelegerd aan de Oude Rijn naar hout en voedsel gemodelleerd en gekwantificeerd voor de periode 40-140 n. Chr. (Hfst. 5). De absolute volumes aan hout en voedsel zijn berekend in m^3 en kCal, en vervolgens omgerekend naar de oppervlakten land die nodig zijn om deze te leveren. De beschikbare hoeveelheid land in het onderzoeksgebied is gekwantificeerd aan de hand van de paleogeografische kaart. Vergelijking van deze waarden laat zien dat de draagkracht van het landschap groter was dan tot nu toe werd aangenomen. Aanvankelijk was de draagkracht van het landschap niet beperkend voor de totale vraag aanbod van zowel leger als lokale bevolking. Doordat de bevolking in de loop van de tijd sterk groeide nam de druk op het landschap toe en werden de productiegrenzen mogelijk bereikt in de loop van de tweede eeuw n. Chr.. Verder laten onze berekeningen zien dat hout en voedsel, met name graan, door de agrarische nederzettingen in de directe omgeving kon worden geproduceerd. De lokale bevolking lijkt dus veel meer betrokken bij de bevoorrading van het Romeinse leger aan de Oude Rijn dan tot nu toe werd gedacht. Het is wel waarschijnlijk dat lokale aanvoer werd gecombineerd met aanvoer van buiten de regio (zowel extra- regionaal als via lange afstandstransport).

In Hoofdstuk 6 worden geologische en archeologische datasets geïntegreerd om te tonen hoe de Oude Rijn en de Kromme Rijn – aanvankelijk de grootste Rijntak – geleidelijk aan werden verlaten (avulsie) en de ontwikkeling van de menselijke bewoningsgeschiedenis van het gebied rondom Utrecht beïnvloedden. Deze studie richt zich op het in fasen verlopende avulsieproces van een natuurlijke rivierarm in samenhang met toenemende menselijke bewoning in de Romeinse Tijd en de Middeleeuwen (1^{e} millennium n. Chr.). Bij deze analyse is gebruik gemaakt van de zeer rijke datasets die voor dit gebied beschikbaar zijn. De geoarcheologisch dataset maken een strakke tijdscontrole voor deze reconstructie mogelijk, waardoor het mogelijk was om de snelheid van de verschillende fasen in het avulsieproces te bepalen. Uiteindelijk was het zelfs mogelijk de veranderingen in rivierdimensies en meanderstijl te kwantificeren en schattingen te maken van de waterafvoer tijdens de verschillende fasen van het ca. 1000 jaar-durende avulsieproces, waarbij de volwassen rivierarm uiteindelijk wijzigde in een gekanaliseerde laatmiddeleeuwse Rijnloop.

De geomorfologische ontwikkelingen tijdens deze periode lijken cruciaal te zijn geweest voor de ontwikkeling van Utrecht van de locatie van een Romeins fort naar een middeleeuws kerkelijk centrum. De bewoningsdynamiek in en rondom de stad Utrecht veranderde tijdens de verschillende fase van het avulsieproces. In het splitsende netwerk van rivierarmen in de Rijn-Maas delta vormde de Oude Rijn de Romeinse grens, de *Limes,* en was een belangrijke transportroute. De splitsing van de Oude Rijn en de Vecht in Utrecht vormde een belangrijke vestigingslocatie voor de bouw van een romeins fort. Tijdens het voortgaande avulsieproces in de Vroege Middeleeuwen veranderde de locatie van het splitspunt. In de Late Middeleeuwen (ca. 800-1000 n. Chr.) namen de overstromingen en sedimentatie tijdelijk sterk toe, waardoor de bewoning op de oevers van de Oude Rijn het gebied zelfs tijdelijk werd verlaten. Vergelijkbare mens-rivier interacties vonden plaats in andere delta's die in het Romeinse Rijk waren opgenomen, zoals de Nijl, Rhône, Po, Donau en Ebro. Daarbij traden echter wel verschillen op als gevolg van de locaties van de bewoning, de hydrologische situatie en de mogelijkheden van de verschillende samenlevingen om het landschap en eventuele veranderingen daarin te beheersen.

De geïntegreerde analyses van fluviatiele afzettingen en archeologische, historische en paleobotanische gegevens van de Rijn-Maas delta hebben de reconstructie van veranderingen in het rivierenlandschap zowel wat betreft datering en fasering als de invloed hiervan op de menselijke bewoning langs de Oude Rijn in de Romeinse Tijd en Middeleeuwen (ca. 1-1100 n. Chr.) sterk verbeterd. Gedetailleerde landschapsreconstructies zijn cruciaal voor het interpreteren van veranderingen in bewoningspatronen en landgebruik, van delta's en laaglandgebieden. Zonder een gedetailleerd begrip van de rivier en de landschappelijke evolutie van een gebied kan de bewoningsgeschiedenis van het betreffende gebied niet op juiste wijze worden geïnterpreteerd.

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Appendix A – Supplement to Chapter 2

Palaeogeographic map of the Limes-zone along the western Lower Rhine, the Netherlands. Scale 1: 50,000, A0-format.

This map is part of the manuscript: Van Dinter, M., 2013. The Roman Limes in the Netherlands: how a delta landscape determined the location of the military structures. *Netherlands Journal of Geosciences – Geologie en Mijnbouw* 92-1, 11-32.
(https://www.cambridge.org/core/journals/netherlands-journal-of-geosciences/article/the-roman-limes-in-the-netherlands-how-a-delta-landscape-determined-the-location-of-the-military-structures/7731E612F9341D39D5587763CAEDE641)

This Appendix is available through https://figshare.com/authors/Marieke_Van_Dinter/4174441, choose Appendix A
or directly https://figshare.com/articles/Appendix_A_Palaeogeographical_map_of_western_Lower_Rhine_The_Netherlands_Van_Dinter_2017_/5151166
or https://www.academia.edu/5169100/Van_Dinter_2013_NJG_92-1_Appendix_1_Limes_map_A0

Map layers are digitally available at DANS EASY:
http://www.persistent-identifier.nl/?identifier=urn:nbn:nl:ui:13-08qf-sf or
https://easy.dans.knaw.nl/ui/datasets/id/easy-dataset:61652

Appendix B – Supplement to Chapter 2

All sources used for the construction of the palaeogeographical map and the archaeological sites of Appendix A.

This is part of the manuscript:: Van Dinter, M., 2013. The Roman Limes in the Netherlands: how a delta landscape determined the location of the military structures. *Netherlands Journal of Geosciences – Geologie en Mijnbouw* 92-1, 11-32.
(https://www.cambridge.org/core/journals/netherlands-journal-of-geosciences/article/the-roman-limes-in-the-netherlands-how-a-delta-landscape-determined-the-location-of-the-military-structures/7731E612F9341D39D5587763CAEDE641)

The catalogue is subdivided in the following topics:

I. Maps
II. Roman river
III. Castella
IV. Small military sites
V. Canals
VI. Settlements (Rural settlements and vici)

Some references contain information on several of the topics these references and therefore referenced in several topics. For comprehensive list of excavations and surveys of the Roman road see Luksen-IJtsma (2010).

This Appendix is available through:
https://figshare.com/authors/Marieke_Van_Dinter/4174441, choose Appendix B
or directly https://figshare.com/articles/Appendix_B_Van_Dinter_2017/5151196

Appendix C – Supplement to Chapter 5

Parameter values and underlying assumptions used in the modelling of the carrying capacity of the Lower Rhine delta.

This is part of the manuscript: Van Dinter, M., L.I. Kooistra, M.K. Dütting, P. van Rijn (†) and C. Cavallo, 2013. Could the local population of the Lower Rhine delta supply the Roman army? Part 2: Modelling the carrying capacity of the delta using archaeological, palaeo-ecological and geomorphological data. Journal of Archaeology in the Low Countries 5-1, 5-50.
(http://jalc.nl/cgi/t/text/get-pdf75d9.pdf?c=jalc;idno=0501a04)

The list of assumptions is subdivided in the following topics:

- Population size
- Military module
- Rural demand and supply

This Appendix is available through
https://figshare.com/authors/Marieke_Van_Dinter/4174441, choose Appendix C
or directly
https://figshare.com/articles/Appendix_C_-_Van_Dinter_2017/5151202

Appendix D – Supplement to Chapter 6

Data underlying the reconstruction of the river channel development of the Utrecht case

This is part of the manuscript: Van Dinter, M., K.M. Cohen, W.Z. Hoek, E. Stouthamer, E. Jansma and H. Middelkoop, 2017. Late Holocene lowland fluvial archives and geoarchaeology: Utrecht's case study of Rhine river abandonment under Roman and Medieval occupation, and its international relevance. 20-yr FLAG special issue on Fluvial Archives, Quaternary Science Reviews 1-39. (https://www.infona.pl/resource/bwmeta1.element.elsevier-afe8ae9a-b150-3aa4-b578-2a039851c12c)

This Appendix contains the following topics:

- Section A: Data – Overview of data underlying the channel development reconstruction of the Utrecht case
- Section B: Reconstruction – Description of channel belts and the data sources from which these are derived

This Appendix is available through
https://figshare.com/authors/Marieke_Van_Dinter/4174441, choose Appendix D
or directly
https://figshare.com/articles/Appendix_D_-_Van_Dinter_2017/5151229

The mother database (digital repository of map data and GIS files) of Appendix D is available through
https://figshare.com/authors/Marieke_Van_Dinter/4174441, choose Appendix D – Originele Moederdatabase Van Dinter 2017
or directly
https://figshare.com/articles/Appendix_D_Originele_Moederdatabase_Van_Dinter_2017/5151151

The digital repository of the GIS files (map layers) is available at DANS EASY through doi:10.17026/dans-zrz-qm5n.

Author's background

I was born on the August 23th 1970 in Uden, The Netherlands. After attending primary and secondary school in this town, I started studying Physical Geography at Utrecht University in 1988. During my study, I became interested in Quaternary Geology and specialized in 'Geomorphology in lowland areas' and 'Palynology and Palaeobotany'. Furthermore, I was fascinated by Archaeology. Therefore, I attended classes in Northwest European Prehistory at Leiden University. Already during my study, I combined these interests. At first during a fieldwork in Greenland (Kangerlussuaq/ Søndre Strømfjord and later by assisting in an archaeological research project of Leiden University supervised by dr. Leo Verhart, drs. Milco Wansleeben and Herman van de Beek (†) in the Roer and Vlootbeek valley (province of Zuid-Limburg). I finished my studies by learning macrofossils with prof. dr. Hilary Birks at the Bergen University, Norway.

After receiving my master degree in 1994, I worked several months as a junior researcher at Utrecht University both at department of Physical Geography and at department of Palynology and Palaeobotany. In 1995, I received a 9-months NUFFIC-scholarship to study Late Glacial lake deposits in southwest Norway (Sunnmøre) at Bergen University.

After my return to The Netherlands, I started to work as a physical geographer in the field of archaeology in the spring of 1997. At first at the Joan Willems Foundation (JWS, part of State Archaeological Service (ROB)), which was converted into a commercial archaeological company in 1998 and renamed into ADC Archeoprojecten. I continued to work here until the present day with much enthusiasm. It is my task to reconstruct palaeoenvironments at archaeological sites to reveal the influence of landscape and its development on human activities in the past. The excavations are carried out in different landscape settings in the Netherlands and cover different time periods.

In 2004, I was asked to join the research project entitled '*A sustainable frontier? The establishment of the Roman frontier in the Rhine delta*' (Dutch Organisation for Scientific Research (NWO), Malta Harvest). This interdisciplinary project focused on the interaction between potential supply provided by the landscape and military requirements in the western part of the Rhine-Meuse delta during the 1st and early 2nd century AD (AD 40-140). Thereto I produced a detailed palaeogeographical map of this section of the Roman *Limes* in The Netherlands.

Between 2009 and 2012, I was part-time (0,2 fte) posted at the department of Geosciences, Utrecht University, as a PhD researcher. This post was funded by the research project entitled '*Treasures of the Dom square; reconstructing Roman and Early-Medieval Utrecht: new approaches*' and is supervised by prof. dr. Esther Jansma. Within this project the faculties of Humanities and Geosciences, the municipality of Utrecht and Intiatief Domplein collaborated in archaeological, historical and geo-scientific research and aimed at positioning the history of the present Dom Square in Utrecht in a wider geographical and cultural context, focussing on the first millennium AD. Within the framework of this project the PhD-thesis was written. Furthermore, the results of Malta Harvest research were incorporated into the thesis. From 2013 until 2017, I was a guest researcher (0,2 fte) at the Utrecht University.