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Best travel options: Modelling Roman and early-medieval routes in the Netherlands using a multi-proxy approach

Rowin J. van Lanen^{a,b,*}, Menne C. Kosian^b, Bert J. Groenewoudt^b, Theo Spek^c, Esther Jansma^{a,b}

^a Utrecht University, Faculty of Geosciences, P.O. Box 80.115, 3508 TC, Utrecht, the Netherlands

^b Cultural Heritage Agency of the Netherlands, P.O. Box 1600, 3800 BP, Amersfoort, the Netherlands

^c University of Groningen, Faculty of Arts, Landscape History, 9712 GK, Groningen, the Netherlands

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ABSTRACT

During the Roman and early-medieval period in the Netherlands, an extensive network of routes connected settlements on the local, regional and supraregional scale. The orientation of these route networks in part was determined by settlement locations, and in part by environmental factors (e.g. soil type, relief). Therefore these route networks provide a key in understanding the dynamic interplay between cultural and environmental factors.

This study focuses on modelling Roman and early-medieval routes using a multi-proxy approach. By combining network friction with archaeological data representing settlements, burial sites and shipping-related finds we wish to investigate the possibilities of using these large-scale datasets for modelling Roman and early-medieval route networks in the Netherlands. Data representing past infrastructure and isolated archaeological finds were used to validate the model output.

Results show that in geomorphologically diverse lowland regions, such as the Netherlands, network friction is extremely useful for modelling historical route networks. We found a clear relationship between environmental conditions, settlement locations and the spatial distribution of infrastructure. Using evidence-based modelling, we were able to correctly predict the location of 89% of the currently identified Roman infrastructure, and 85% of the known early-medieval infrastructure in the Netherlands within a 1000 m buffer. Additionally, despite only roughly covering a surface area of 13% in the Roman and 11% in the early-medieval period of the Netherlands, 82% and 72% of all known isolated finds were located within the same buffer.

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1. Introduction

The Netherlands is a dynamic lowland region partially influenced by fluvial (e.g. Rhine, Meuse and Scheldt) and marine activity. The west and north of the country are low-lying regions which have been subjected to flooding throughout the Holocene (Stouthamer and Berendsen, 2000; Erkens, 2009; Vos et al., 2011; Cohen et al., 2012; Toonen, 2013; Vos and De Vries, 2013). The central, eastern and southern parts can be regarded as relatively stable landscapes largely consisting of somewhat higher Pleistocene soils (Steur and Heijink, 1991; De Vries et al., 2003; Koomen and Maas, 2004).

Recent research shows that major landscape changes (e.g. vegetation, flooding) occurred during the transition from the Roman period (12 BC–AD 450) to early-medieval period (AD 450–1050) (Stouthamer and Berendsen, 2000; Roymans and Gerritsen, 2002; Groenewoudt et al., 2007; Erkens, 2009; Groenewoudt, 2012; Jansma et al., 2014;

Toonen, 2013). Archaeological evidence from these periods suggests simultaneous alterations in land use and settlement patterns as well as severe demographic decline (Cheyette, 2008). Historical route networks, which are the product of and influenced by both cultural and landscape dynamics, provide a key to understanding the nature of and interaction between these dynamics. Our own research on landscape prerequisites of potential Roman and early-medieval routes in the Netherlands shows clear differences in regional accessibility during these periods (Van Lanen et al., 2015). The western and northern parts would have been largely inaccessible by land and settlements in these regions must have been highly dependent on water transport. Additionally, in these regions landscape changes were most extreme from the Roman to early-medieval period as compared to other parts of the Netherlands (Van Lanen et al., 2015).

In recent years the reconstruction of historical roads, or more generally historical route networks, has been attempted frequently using spatial modelling and Geographical Information Systems (GIS) software (e.g. Gietl et al., 2008; Zakšek et al., 2008; Verhagen and Jeneson, 2012; White and Barber, 2012; Verhagen, 2013; Breier, 2013). Mostly focussing either on elevated regions where relief to a large extent

* Corresponding author at: Utrecht University, Faculty of Geosciences, P.O. Box 80.115, 3508 TC, Utrecht, the Netherlands.

E-mail address: r.van.lanen@cultureelerfgoed.nl (R.J. van Lanen).

determines route orientation or on improving our theoretical understanding of how to model past routes, these papers mainly addressed the correct definition of tools such as friction layers, viewshed analyses and least-cost paths (Verhagen, 2013).

However, the usefulness of these approaches is limited when applied to lowland regions. In these areas, which are marked by small relief differences, other landscape characteristics equally determine route orientation (e.g. the presence of mires, natural peat bogs or rivers). Therefore a different approach is needed. This is why the present study uses a network-friction model (NFM) to combine data on past environments with archaeological data, in order to reconstruct Roman and early-medieval route networks. Network friction is the variable that determines potential regional accessibility based on the comparison of local and surrounding landscape factors (Van Lanen et al., 2015). The NFM for the Netherlands was developed by Van Lanen et al. in 2015 and combines numeral environmental datasets in order to calculate landscape prerequisites for Roman and early-medieval routes. Based on landscape factors, this model identifies and locates transport obstacles and movement corridors for the Roman period and Early Middle Ages. The central aim of this second study is to determine the extent to which movement corridors calculated by the NFM and data on settlement patterns can be integrated to model historical route networks in the Netherlands. The focus of the research is not on cultural interpretation but much more on methodology; specifically the potential of large-scale datasets and the benefits of an evidence-based, integrated approach.

2. Theoretical background

Routes are not roads, and route networks fundamentally differ from road networks. The evidence for the presence of actual roads in the Roman and early-medieval Netherlands is limited. Where roads can be regarded as fixed features connecting two places, routes are frequent-travel zones. Almost all Roman period and early-medieval roads were unpaved and not fixed to one location (e.g. Horsten, 2005). Seasonal (e.g. weather) or yearly (e.g. general wear) conditions could force travellers to shift to other adjacent lanes, creating a route zone. Therefore route networks are more spatially dynamic but in general orientation equal to road networks.

Landscape is constantly and inevitably changing through the influence of human and natural factors and the complex and dynamic interaction between them (Fairclough, 2007). Route networks are subjected to both these cultural and environmental factors and as such provide a key to better understand and study their dynamic interplay. The study of large-scale route networks requires a landscape-archaeological approach since these networks transcend the traditionally studied site level and require a focus on both cultural and environmental variables.

Landscape archaeology is best defined as the interdisciplinary investigation of the long-term relationship between people and their environment (Barker, 1986; Kluiving et al., 2012; Kluiving and Guttmann-Bond, 2012). The disciplines used in landscape archaeology have in common that the dynamics of past landscapes are investigated as that of one single, complex research entity. “Landscape” within this context is best defined at a basic level as: “an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors” (Council of Europe, 2000). In order to model past route networks and settlement patterns, both the natural (e.g. landscape dynamics, climate) and cultural (e.g. economy, politics) processes within these landscapes need to be sufficiently understood. Landscape archaeology is multi-disciplinary “by nature” and as such it is a perfect tool to study the interaction between physical and cultural processes.

Traditional GIS modelling of past routes has largely focussed on correctly defining cost-surface modules (Zakšek et al., 2008; Herzog and Posluschny, 2008; Murrieta-Flores, 2012; Herzog, 2013a,b,c; Verhagen, 2013; Herzog, 2014). In low-lying regions such as the Netherlands these approaches are less useful when modelling route networks. In these regions, other landscape factors greatly will have

determined route networks and local translocation conditions (e.g. the presence of mires, peat bogs, rivers). Network friction calculates regional accessibility conditions based on environmental data and locates transport obstacles and corridors, and therefore can be used to model historical route networks (Van Lanen et al., 2015). Past route networks can be modelled and tested by combining network friction with archaeological data on e.g. settlements and infrastructure.

Due to cultural and environmental variables, settlements were never distributed equally throughout a region, which results in spatially variable settlement densities. Densely-settled areas can be expected to trade and communicate with nearby settlements and with other densely-settled areas a little further away and as such are expected to function as central hubs within dynamic systems.¹ Therefore these High-Density Settlement Clusters (HDSCs) are crucial for modelling route networks. HDSCs were determined based on the ratio of sites per square kilometres (s/km²) in order to keep the NFM evidence based and to minimize archaeological-theoretical modelling. Settlements outside HDSCs (in this paper referred to as isolated settlements) are individual elements within the route network. Since either these settlements were founded near existing routes, or routes developed near existing settlements, they can be regarded as indicative of supra-regional route orientation.

In addition to following geographical transport corridors, people moving through the landscape preferably will have avoided uncultivated areas. The reason is that these regions most likely were less accessible because of soil and vegetation conditions (respectively e.g. mires and dense forests) and might also have been regarded as ‘no-go areas’ (Roymans, 1995; Spek, 2004; Kolen, 2005). If possible, travellers will have used settled areas (i.e. the settlement area including surrounding cultivated lands) as much as possible. This is why the settled areas of isolated settlements can be utilized for modelling route orientation.

3. Material

3.1. Network Friction Model (NFM)

Van Lanen et al. (2015) already determined geographical obstacles and corridors for possible translocation in ca. AD 100 and 800 (Fig. 1). The resulting NFM integrates palaeogeographical data from the Roman and early-medieval period (Bos, 2010; Vos et al., 2011; Cohen et al., 2012; Van Dinter, 2013; Vos and De Vries, 2013). Contemporary landscape data was added using the geomorphological and soil maps of the Netherlands. The geomorphological map (1:50,000) contains information on the relief, genesis and age of landscape elements (Koomen and Exaltus, 2003; Koomen and Maas, 2004). The soil map (1:50,000) provides an overview of current soil types and average groundwater levels (Steur and Heijink, 1991; De Vries et al., 2003; Van der Gaast et al., 2010). Landscape units postdating the Early Middle Ages were removed from both datasets. Elevation data for the Pleistocene soils was added through the Height Model of the Netherlands (AHN) (Brand et al., 2003; Swart, 2010; Van der Zon, 2013).

3.2. Archaeological data

Archaeological data representing settlements, burial sites, shipping (e.g. ships, canoes) and isolated finds were collected through the Archaeological Information System of the Netherlands (ARCHIS). This system contains a national overview of archaeological finds (Roorda and Wiemer, 1992; Wiemer, 2002).² In order to obtain maximum accuracy, the ARCHIS data were compared to the results of new research published in PhD theses, books and research reports (Miedema, 1983;

¹ The assumption of movement from these HDSCs is in line with the complex, dynamic interaction between people and landscape (e.g. Kolen, 1995; McGlade, 1999).

² ARCHIS is maintained by the Cultural Heritage Agency of the Netherlands (RCE) and was created in 1992. Website: <http://archis2.archis.nl/>.

Fig. 1. Network-friction land maps: AD 100 and 800 (adapted from Van Lanen et al., 2015).

Knol, 1993; Bechert and Willems, 1995; Verwers, 1998; Van Beek, 2009; Gerrets, 2010; LGL World Heritage Database, 2010; Verlinde and Hulst, 2010; Dijkstra, 2011; Van der Velde, 2011). In order to enhance the quality of the ARCHIS dataset we digitized and imported these data into the NFM and applied selection filters (Van Lanen et al., 2015).

4. Method

4.1. Determining High Density Settlement Clusters (HDSCs)

We defined HDSCs as regions in which the ratio of settlements per square kilometre (s/km^2) is higher than the average settlement density in the research area (Section 2). Only proven settlements (archaeologically well-dated sites with a find complex >5) were included in the analysis (Van Lanen et al., 2015). Since we assume that all settlements are equal parts of route networks and the size of settlements is usually unclear, no division was made between larger and smaller settlements.

4.1.1. Roman High Density Settlement Clusters (HDSCs)

Roman-period settlement patterns in north-western Europe have been studied extensively during the last two decades (e.g. Taayke, 1996; Hiddink, 2005; Williams, 2007; Van Beek, 2009; Vos, 2009; Gerrets, 2010; Van Beek and Groenewoudt, 2011). Van Beek and Groenewoudt (2011) have used many of the resulting overviews to compare Roman settlement patterns in the stream valley of the river Vecht to other nearby regions. They state that (p. 180) "... data in this table are probably biased by the fact that the regions listed here attracted particular archaeological attention because they are rich in archaeological sites." In other words these regions can be regarded as densely settled areas (i.e. areas with relatively high number of settlements, not necessarily population). We therefore used the average s/km^2 of these regions to determine HDSCs (Table 1).

Since the NFM uses a grid-cell resolution of 500×500 m, we assumed that multiple sites located within a single grid cell together represent one individual settlement (Van Lanen et al., 2015). In order to compensate for any discrepancy in recorded location coordinates, we placed settlements at the centre of the grid cells. This approach results in a maximum deviation of 250 m for each settlement location.

Using settlement-density data from Table 1 we calculated an average settlement density of 0.65 settlements per $1 km^2$, in other words 1 settlement per $1.538 km^2$ (Fig. 2).

For the Roman period this implies that the average total distance between two settlements in a HDSC may never exceed 1.538 km. Settlements in regions where the average total distance exceeds this 1.538 km are regarded as isolated settlements.

4.1.2. Early-medieval High Density Settlement Clusters (HDSCs)

For north-western Europe no large-scale overviews of early-medieval settlement patterns are available. To enable comparison between settlement ratios of the Roman and early-medieval periods, we made use of the concept of the *archeoregio* (archaeological region) (Groenewoudt, 1994; Lauwerier and Lotte, 2002; Van Dockum and Lauwerier, 2004; Van Dockum et al., 2006). These regions are defined as areas with

Table 1

Ratio sites per square kilometres (s/km^2) for regions in northwest Europe (adapted from Van Beek and Groenewoudt, 2011, p. 180). Data for Kent (UK) was adapted from Williams (2007).

Region	Surface (km^2)	N rural settlements	Sites/ km^2
Kromme Rijn (NL)	110	120	1.09
Tiel (NL)	105	94	0.89
Eastern part of the Dutch central River area (NL)	1650	510	0.30
Köln, Bonner Niederterrasse (DE)	77	28	0.36
Bladel (NL)	175	40	0.22
Somerens (NL)	72	25	0.34
Lieshout (NL)	75	22	0.29
Maashorst (NL)	100	19	0.20
Kempener Lehmplatte (DE)	243	38	0.16
Aldenhovener Platte (DE)	35	69	1.90
Xanten (DE)	1252	181	0.14
Westergo (NL)	374	712	1.85
Oostergo (NL)	190	171	0.90
Overijsselse Vecht (NL)	294	45	0.18
Kent (UK)	xxx	xxx	1.00
		Total	9.82
		Total average	0.65

Fig. 2. Overview of High Density Settlement Clusters (HDSCs) overlaid on a relief map of the current in the Netherlands; A: Roman period; B: Early Middle Ages.

specific archaeological and environmental characteristics (e.g. southern-cover sands, river area; Fig. 3). Per *archeoregio* the total surface and total number of sites were determined (Table 2).

The ratio between the averages for the Roman and early-medieval periods (0.084 and 0.056 respectively) is 1.5 and was used to extrapolate the settlement density for HDSCs in the Early Middle Ages:

Roman period	Early Middle Ages
Ratio <i>archeoregio</i> 's: 0.084	Ratio <i>archeoregio</i> 's: 0.056
Regional studies: 0.65	Extrapolated: 0.43
Settlement density Roman period: 1.5× compared to the Early Middle Ages	

Based on this ratio we calculated an average settlement density of 0.43 per km² for the Early Middle Ages, in other words 1 settlement per 2.325 km² (Fig. 2). Therefore for the Early Middle Ages the total distance between 2 settlements in a HDSC may never exceed 2.325 km. Settlements in regions where the average total distance exceeds 2.325 km are regarded as isolated settlements.

This quantitative approach does not select individual (larger) settlements that function as political, economic or religious centres outside the HDSCs and have a similar influence on route orientation. The majority of these centres are known through historical sources and/or archaeological research. Therefore in order to compensate for the large influence of the Roman army on local economy, infrastructure, trade and building activities south of the river Rhine (which functioned as the Roman frontier), the NFM was expanded by defining Roman towns, (legionary) fortresses (*castra* and *castellae*) and larger military sites published by Bechert and Willems (1995) and LGL World Heritage Database (2010) as hubs (i.e. of equal importance as HDSCs). Additionally, Hiddink (1991) showed the importance of rural centres

to local economies south of the Roman frontier. If located outside the HDSCs, these settlements also were added to the NFM (Appendix A).

Early-medieval settlement patterns have been studied less extensively than Roman settlement patterns. For this period overviews are lacking. Historical sources refer to two *emporium* within the Netherlands: Dorestad and Witla (e.g. Alcuin, *carmina* IV; *Annales Fuldenses*; Dijkstra, 2011). Dorestad, located near the current city of Wijk bij Duurstede, was added to the network. Although the precise geographical location of Witla is still unknown historical sources situate the small *emporium* near the coast in the Meuse estuary and as such Witla would be part of an already identified HDSC. Other archaeologically classified central settlements, not part of a HDSC, also were added to the NFM (Appendix A).

4.2. Settled areas

Without “interference” from landscape characteristics and nearby isolated settlements, route networks ideally consist of straight lines between HDSCs (Fig. 4, point 1).³ Routes however were never straight lines since route networks also connect HDSCs with settlements situated in-between HDSCs. These settlements were more spatially isolated compared to the settlements within the HDSCs, but we may assume that they were very much part of the route network. Since new settlements can be expected to be generally founded in the vicinity of existing routes, or routes developed near existing settlements, their spatial distribution (in addition to the landscape settings) is a strong indication of route orientation outside the HDSCs (Fig. 4, point 2).

³ The naïve but fundamental assumption of these straight lines forms the basis of many geographical network models. For more information: Chorley and Haggett, 1968.

Fig. 3. Overview of archaeological regions (*archeoregio's*) in the Netherlands.

Settled areas consist of off-site cultivated lands (i.e. arable land directly surrounding the settlement, plus pastures and wood-gathering areas) and the actual settlement (site) (Von Thünen, 1842; Foley, 1978, 1981). Translocation preferably will have taken place within settled areas. It is assumed that uncultivated regions outside settled areas (e.g. forests, mires) would have been avoided as they were difficult to travel through and often were regarded as no-go areas (Section 2). We expect people to have preferred the shortest route between settled areas.

To determine the size of the cultivated lands we created a buffer around each known Roman and early-medieval settlement. The average distance between settlements in the Roman period is 1.538 km (Section 4.1). With a maximum deviation of 250 m in settlement location, the buffer around each settlement equals:

$$\text{Maximum distance}/2 + \text{maximum deviation grid-cell resolution} \\ 1.538/2 + 250 \text{ m} = 1.019 \text{ km.}$$

For the early-medieval period, the average distance between settlements is 2.325 km (Section 4.1). With the same maximum

deviation of 250 m in settlement location the buffer for each early-medieval settlement equals:

$$2.325/2 + 250 \text{ m} = 1.413 \text{ km.}$$

It is argued that in the Netherlands (at least) 50% of the settlements are not (yet) discovered (Bult, 1983; Deebe et al., 2006). To compensate for this discrepancy of (at least) 50% the buffers (settled areas) of the known settlements were extended and multiplied by 2: a settled area of 2.038 km for Roman and 2.826 km for early-medieval settlements. Although the precise location of the undiscovered settlements is unknown, the settled areas from these settlements would probably intersect these larger buffers. Routes can then be calculated based on these larger settled areas.

4.3. Modelling land routes

Route networks consist of land and/or water routes. Corridors for water transport (e.g. rivers) often function as obstacles for land

Table 2

Overview of the surface area, number of Roman and early-medieval settlements and the ratio between them per *archeoregio*. Archaeological regions highlighted in dark grey either post-date the Early Middle Ages, contain no data, or are located outside our research area and where not included in the average.

Archaeological region (<i>archeoregio</i>)	Surface km ²	N Settlements (Roman period)	Ratio: Settlements/surface Roman period	N Settlements Early Middle Ages	Ratio: Settlements/surface Early Middle Ages
Sandy area Drenthe	5034	53	0.011	19	0.004
Sandy area Utrecht & Gelderland	2984	101	0.034	59	0.020
Sandy area Overijssel & Gelderland	3912	148	0.038	115	0.029
Sandy area Brabant	5000	342	0.068	168	0.034
Sandy area Limburg	784	138	0.176	25	0.032
Loess area Limburg	597	5	0.008	2	0.003
Peat area Friesland	1514	7	0.005	13	0.009
Holland dune area	654	58	0.089	76	0.116
Holland peat and clay area	2883	80	0.028	66	0.023
Utrecht & Gelderland rivers area	2366	631	0.267	204	0.086
Voordelta/streams Zeeland	2458	1	0.000	1	0.000
Waddenzee/IJsselmeer-Markermeer	4728	1	0.000	1	0.000
Clay area Friesland & Groningen	2883	530	0.184	767	0.266
Clay area Noord-Holland	1186	94	0.079	42	0.035
Clay area Flevoland	1470	0	0.000	0	0.000
Clay area Zeeland	3576	61	0.017	59	0.016
		Average Roman period	0.084	Average Early Middle Ages	0.056

routes. Therefore it is necessary to model land and water routes separately.

4.3.1. Implementing network friction

Network friction identifies landscape obstacles and corridors for possible translocation (Van Lanen et al., 2015). We modelled the most efficient path between HDSCs and isolated settlements (Section 4.1) using settled areas (Section 4.2) and network friction (Fig. 4, point 3), 'most efficient' being defined here as the shortest possible route between settlements following the highest (i.e. less friction) possible network-friction values.

4.3.2. Burial sites

During the Roman and early-medieval periods burial sites were located in the direct vicinity of settlements (Van Es, 1981; Verlinde, 1987; Verwers, 1998; Heeren, 2009; Van Beek, 2009).⁴ In order to compensate partially for the 50% gap in known settlement locations (Section 4.2) we used isolated burial sites (i.e. burial sites located outside any known settled area) as indicative of as yet undiscovered settlement locations nearby.

4.3.3. Determining land routes

Land routes are determined by the interaction between settlement patterns including burial sites and network-friction values. Following the most efficient paths we modelled route networks based on

⁴ Little large-scale research has been done on the spatial relationship between settlements and burial sites. Extensive research by Verlinde (1987) and Van Beek (2009) for the eastern Netherlands shows burial sites moving from an average distance of >500 m from settlements in the Iron Age to an average distance of <200 m in the Roman period. Research done by Hiddink (2003) for the southern Netherlands show a similar distance of 200–300 m.

solid archaeological data (Fig. 5). Positive network-friction values ('reasonably accessible' to 'accessible') allow for other possible routes following movement corridors in the network but were not included (Fig. 5).

In Holocene parts of the Netherlands network-friction values are generally lower. In these regions small levees often produced accessible corridors, which compared to other parts of the country might have been less attractive for movement, but locally still must have offered the best travel options. Here the highest network-friction values were selected (Fig. 6). Fig. 7 shows national overviews of land-routes en networks for AD 100 and 800.

4.4. Modelling water routes

In order to model water routes Van Lanen et al. (2015) created network-friction water maps for AD 100 and 800 (Fig. 8). Network-friction values from these maps were combined with the archaeological data representing settlements and shipping-related finds.

4.4.1. Implementing network friction

The geographical situation of the Netherlands as a coastal lowland already hints at the importance of water transport. Rivers in the Netherlands frequently have been described as highways of the past (e.g. Van Es and Verwers, 2010; Dijkstra, 2011). Using palaeogeographical data we located corridors for water transport (i.e. rivers with sufficient carrying capacity; Fig. 8). We modelled water routes by combining network friction with the HDSCs, isolated settlements and ship-related finds into one NFM (Fig. 4, points 6–7).

4.4.2. Shipping-related finds

Shipping-related finds (e.g. ship wrecks, re-used ships timbers) are an indication for trade routes. We extracted these finds from the

Fig. 4. Flowchart of modelling historical-route networks. (1) Direct lines exist between High Density Settlement Clusters (HDSCs). In this situation isolated settlements and the environment have no influence on route orientation. (2) Isolated settlements are introduced into the model and influence route orientation. (3) Route orientation is further influenced by environmental settings (land) as modelled by network friction. (4) Burial sites are introduced and further influence route orientation. (5) Buffers of 500, 1000 and 2000 m are created. (6) Route orientation is further influenced by environmental settings (water) as modelled by network friction. (7) Shipping-related finds are introduced and further influence route orientation. (8) Buffers of 500, 1000 and 2000 m are created. (9) Land and water-route zones are combined. (10) Modelled results are tested against infrastructural finds. (11) Modelled results are tested against isolated finds.

Fig. 5. Route modelling in the eastern Netherlands (AD 800). Routes are reconstructed based on the most efficient paths between network-friction values, settlement patterns and burial sites. The higher elevated Pleistocene soils are relatively accessible and have high network-friction values.

Fig. 6. Route modelling in the western Netherlands (AD 800). Routes are reconstructed based on the most efficient paths between network-friction values, settlement patterns and burial sites. The low-elevated Holocene soils are relatively less accessible and have low network-friction values.

Fig. 7. Land-route networks in the Netherlands: AD 100 and 800.

ARCHIS database and the dendrochronological e-depot DCCD (Jansma et al., 2012; Jansma, 2013).⁵ The combined overview of water-bordering settlements and ship-related finds was used to model Roman and early-medieval water-route networks.

⁵ The DCCD repository amongst other contains hundreds of datasets derived from dendrochronological research in the Netherlands. It is available through: <http://dendro.dans.knaw.nl>.

4.4.3. Determining water routes

Using the most efficient path between settled areas we modelled the most efficient routes (rivers and sea) between water-bordering HDSCs and isolated settlements (Fig. 9). Only water-bordering settlements (settled areas intersecting with water units) were included in the analyses. Although the number of possible movement corridors for water routes are higher, we limited the modelled routes to those that were underpinned by solid settlement data (Fig. 9). Fig. 10 shows a national overview of water-routes networks for AD 100 and 800.

Fig. 8. Network-friction water maps: AD 100 and 800 (adapted from Van Lanen et al., 2015).

4.5. Combining land and water routes

Route networks consist of land and water routes. Movement within a route network was neither limited to land or water (e.g. travelling on foot, horse, cart or canoe and ship). In order to model and test the Roman and early-medieval route networks we integrated the routes modelled in the previous sections (4.3.3. and 4.4.3.) (Fig. 4, point 9).

4.6. Route validation

The route networks were tested on three scales. Buffers were laid around the projected route lines of 500, 1000 and 2000 m (Fig. 4, Sections 5 and 8). These buffers created effective route zones of 1000, 2000 and 4000 m wide. The 500 metres buffer is the most accurate test because it is equal to the NFM grid-cell resolution (500 × 500 m) with a maximum deviation of half a grid cell (250 m) on both sides.

Fig. 9. Water-route modelling in the western Netherlands. Routes are reconstructed based on the most efficient paths between network-friction values, settlement patterns and ship-related finds. Network friction calculates the accessibility of past rivers.

Fig. 10. Water-route networks in the Netherlands: AD 100 and 800.

The 1000 metre buffer is the sum of both deviation zones plus the route buffer of 500 m. The 2000 metre buffer is much less accurate but was used to test route orientation. Infrastructural finds outside these zones clearly differ in orientation from the modelled route networks

4.6.1. Infrastructure validation

So far we excluded archaeological data on infrastructure in order to validate the NFM output. Data on infrastructure was extracted from ARCHIS (Appendix B). Description quality within ARCHIS varies. Since individual checks of each registered infrastructural find was beyond the scope of this paper, all Roman and early-medieval infrastructural finds were included. This means that both land, water-related and undefined but dated infrastructural finds were used to test the NFM results.

For the Roman period, 742 infrastructural finds were available. The vast majority of finds are located south of the Roman frontier ($n = 665$), against a mere 77 finds to the north. For the Early Middle Ages 103 infrastructural finds were selected.

4.6.1.1. Infrastructure validation Roman period. Using GIS we applied a buffer of 500, 1000 and 2000 m onto the modelled-route network. The location of the infrastructural finds was then compared with these buffers using the following query:

```
Infra_finds_ROM.obj WITHIN Buffer_ROM_X.obj
```

This query analyses all Roman infrastructural finds and selects those which are located within the buffer X ("X" being the buffer size of 500, 1000 or 2000 m). Infrastructural finds outside the route zones were selected using the following query:

```
Infra_finds_ROM.obj WHERE not Obj WITHIN any (SELECT Obj
from Buffer_ROM_2000)
```

4.6.1.2. Infrastructure validation early-medieval period. Using the same buffer sizes and queries, the 103 early-medieval infrastructural finds were tested against the modelled-route network.

```
Infra_finds_VME.obj WITHIN Buffer_VME_X.obj
```

Again, this query selects those infrastructural finds located within buffer X ("X" being the buffer size of 500, 1000 or 2000 m), but in this case it selects finds from the early-medieval period. Infrastructural finds outside the route zones were selected using the following query:

```
Infra_finds_VME.obj WHERE not Obj WITHIN any (SELECT Obj
from Buffer_VME_2000)
```

4.6.2. Isolated finds

Isolated finds cannot be linked to a specific type of archaeological complex (e.g. settlement). However they do indicate local human activity. If our modelled route networks do indeed represent frequent-travel zones, these networks are expected to contain a relatively high percentage of isolated finds despite the fact that they only cover a fraction of the total surface area of the Netherlands (Section 5). Therefore the percentage of isolated finds present in the calculated buffer can be indicative for the NFM accuracy. The same buffers sizes and queries were used to test the route network against the presence of isolated finds. For each of the validation scales the total surface area of the route networks was compared to the surface area of the Netherlands.

```
Isolated_finds_ROM.obj WITHIN Buffer_ROM_X.objand
```

```
Isolated_finds_VME.obj WITHIN Buffer_VME_X.obj
```

In both queries the number of isolated finds within a specific buffer are selected ("X" representing the 500, 1000 or 2000 m buffer).

5. Results

The Roman and early-medieval route networks in the Netherlands included both land and water routes (Section 4.5). Fig. 11 shows an overview of Roman and early-medieval routes in the Netherlands. These networks were used to fully test the model with archaeological data related to infrastructure and isolated finds. The route networks were validated on four different scales: the percentage of infrastructural or isolated finds within a 500 m, 1000 m and 2000 m buffer and the percentage of finds located outside the 2000 m buffer.

Fig. 11. Route networks (land and water) in the Netherlands: AD 100 and 800.

5.1. Results: infrastructural finds

The total number of finds representing Roman infrastructure is 742. A total of 544 infrastructural finds (73.6%) is located within the most accurate buffer of 500 m (Table 3; Fig. 12). Increasing the buffer to 1000 m improves the outcome significantly to 89.2% (658 infrastructural finds) (Table 3; Fig. 12). The least accurate validation of a 2000 m buffer provides a 4.9% increase of correctly modelled infrastructural finds to 94.1% (698 finds) (Table 3; Fig. 12). The modelled Roman route network fails to correctly model 44 finds located outside the least accurate 2000 m buffer (5.9%) (Table 3; Fig. 12).

The total number of finds representing early-medieval infrastructure is 103. A total of 81 infrastructural finds (77.7%) is located within the most accurate buffer of 500 m (Table 3; Fig. 12). When the scale is increased to the 1000 m buffer results improve to 85.4% (89 finds) (Table 3; Fig. 12). A further increase of the buffer to 2000 m only slightly improves the results to 88.3% (92 finds) located within the route-network buffer (Table 3; Fig. 12). The route network fails to correctly model 11.7% (11 finds) of the infrastructural data (Table 3; Fig. 12).

For the Early Middle Ages the 500 m buffer yields slightly more accurate results than it does for the Roman period (4.1% increased accuracy; Fig. 12). The buffers of 1000 m and 2000 m are slightly more accurate for the Roman period. The precision of the defined buffers is lowest for the early-medieval period, modelling 11.7% of infrastructure incorrectly (Table 3; Fig. 12).

5.2. Results: isolated finds

For the Roman period we used 13,731 isolated finds (100%) dispersed throughout the Netherlands for validation. The most accurate buffer of 500 m correctly models 8609 isolated finds as located within 7.2% of the surface area of the Netherlands (64.1% of the finds; Table 4; Fig. 13). Results improve by 17.6% to 81.7% (11,153 isolated finds) within 13.7% of the total surface area when the buffer is increased to 1000 m (Table 4; Fig. 13). The least accurate buffer of 2000 m contains 90.6% (12,402) of the isolated Roman-period finds, and covers 24.4% of the total surface area (Table 4; Fig. 13). The route networks fail to correctly model 9.4% (1329 isolated finds) located outside the 2000 m buffer, which covers 75.6% of the total surface area (Table 4; Fig. 13).

For the early-medieval period 4607 isolated finds dispersed throughout the Netherlands were used to validate. The 500 m buffer, which covers 6.11% of the total surface area of the Netherlands, contains 2469 isolated finds (52.4% of the finds; Table 4). Increasing the scale to the 1000 m buffer, covering 11.9% of the Dutch surface area, improves the results with 19.8% to 72.2% (3361) of the isolated finds located within the buffer (Table 4; Fig. 13). The 2000 m buffer, covering 22.1% of the Dutch surface area, contains 87.8% (4085) of all early-medieval isolated finds in the Netherlands (Table 4; Fig. 13). The route network fails to correctly model 12.2% (522) of the isolated finds located outside the 2000 m buffer, which covers 77.9% of the Dutch surface area.

For the Roman period the 500 m, 1000 m and 2000 m buffers test slightly better than for the Early Middle Ages (Table 4; Fig. 13). The precision of the defined buffers is lowest for the early-medieval period,

Table 3
Overview of test results for Roman and early-medieval infrastructure. For each route zone the percentage of correctly modelled infrastructural finds within the route network is given.

Route buffer	Roman period		Early Middle Ages	
	Number of infrastructural finds	% finds within buffer	Number of infrastructural finds	% finds within buffer
500 m	544	73.6%	81	77.7%
1000 m	658	89.2%	89	85.4%
2000 m	698	94.1%	92	88.3%
Outside 2000 m	44	5.9%	11	11.7%
Total	742	100.0%	103	100.0%

Fig. 12. Percentage of infrastructural finds within and outside the 500 m, 1000 m and 2000 m buffers. Dark grey: Roman period; light grey: Early Middle Ages.

Fig. 13. Percentage of isolated finds within and outside the 500 m, 1000 m, 2000 m buffers. Dark grey: Roman period; light grey: Early Middle Ages.

modelling 12.2% of the isolated finds incorrectly (Table 4; Fig. 13). This might be explained by the fact that the Roman period is characterized by a higher number of settlements, isolated finds and a larger route-network surface area.

6. Discussion

The NFM combines environmental and archaeological data and as such allows modelling of historical route networks. By combining network friction with archaeological data on settlements, burial sites and shipping-related finds, over 86% of the route orientation within a 1 km zone was accurately determined for both the Roman and early-medieval periods. These excellent results might improve further by enhancing the current grid-cell resolution with detailed micro-regional research data.

Micro-regional research data would also allow the modelling of large-scale route networks within the HDSCs. Currently, due to the grid-cell resolution and settlement density the land and water routes in these regions were not modelled. By introducing detailed regional data to the NFM and enhancing the grid-cell resolution these regional routes can be calculated and might increase the models output.

The current NFM clusters and generalizes many landscape units, which is of direct influence on the models resolution (Van Lanen et al., 2015). Although the current study correctly models many routes the accuracy of the NFM might benefit from a more detailed segregation of different soils based on high-resolution regional data. For example network-friction values for peat may differ spatially (Van Lanen et al., 2015), which is mainly due to variations of local vegetation and drainage conditions (e.g. De Bont, 2008). When modelling large-scale route networks this segregation is not essential. For example, we tested both modelled route networks with a minimum and maximum peat coverage for AD 100 and 800 using palaeogeographical data and results never deviated more than 1%.

HDSCs prove very useful as start- and endpoints of the modelled route networks (Sections 4.1 and 5). However the NFM would benefit from a more substantiated approach in determining HDSCs through

the development of e.g. cultural models. The current quantitative approach using archaeological regions compares large areas and as such lacks regional detail. This however is not a problem when modelling long-distance routes. Additionally, since both the Roman and early-medieval periods were analysed using the same approach, the ratio between settlement patterns will remain the same.

Settlements are never equally distributed and differ chronologically and in location. Currently the NFM functions on two times slices (AD 100 and 800). The NFM would benefit from more detailed (regional) palaeogeographical data to model settlement and route dynamics. However the high success rate of our model (Table 4) indicates that new or shifting settlements probably usually were located near already existing routes, and as such will have exerted little influence on large-scale route orientation.

Using isolated finds for testing route networks poses a methodological risk, since such finds relate to human activity of which the nature is undetermined. The results however show that these finds spatially are clustered predominantly within the route networks we established (Table 4, Figs. 12 and 13). The implication is that isolated finds are suitable for testing the models accuracy.

Rivers in the Netherlands were used extensively for both regional and long-distance trade. However land transport should not be underestimated since travelling on foot (e.g. with livestock) or by cart must have been common during both the Roman and early-medieval periods. Roman representations of this mode of transport can be found on monuments (e.g. Trajan's column, Igel monument), *milliaria* (i.e. milestone) and in historical sources (Seneca *de epistulae morales ad lucilium*, letter 57; Gijsbers, 1999; Doorewaard, 2010). Despite the lack of evidence for early-medieval land transport, which is related to the difficulty of finding and dating paths and the re-use of broken-down carts as e.g. fire wood, we can assume frequent land transport for this period. Therefore the NFM has been designed to model both land and water routes.

Archaeological data in ARCHIS collected prior to its development in 1992 are not always (fully) recorded. Additionally, new research often extracts, enhances and corrects original data. Currently the feedback

Table 4

Overview of the test results regarding Roman and early-medieval isolated finds. For each route zone the percentage of correctly modelled isolated finds and total surface area of the route network is given.

Route buffer	Roman period			Early Middle Ages		
	Number of isolated finds	% finds within buffer	% surface area Netherlands	Number of isolated finds	% finds within buffer	% surface area Netherlands
500 m	8609	64.1%	7.2%	2469	52.4%	6.11%
1000 m	11,153	81.7%	13.7%	3361	72.2%	11.9%
2000 m	12,402	90.6%	24.4%	4085	87.8%	22.1%
Outside 2000 m	1329	9.4%	75.6%	522	12.2%	77.9%
Total	13,731	100.0%	100.0%	4607	100.0%	100.0%

of these new data into ARCHIS is limited, which implies that the ARCHIS datasets not always are up-to-date or complete. To counter this problem we first digitized all newly available archaeological (overview) studies (Section 3.2) and compared these data with the ARCHIS dataset. Next, we only included settlements with a proven find complex of 5 or more dateable finds, to ensure the exclusion of the majority of spatially and chronologically doubtful settlements.

Cult sites were not included in the NFM. Therefore the model does not reconstruct religious routes and focuses on large-scale route networks only. To what degree these religious routes differed from the reconstructed route networks cannot be assessed at this point. However, in combination with archaeological theoretical models, data regarding cult sites might be added to the NFM in order to model these religious routes and add detail on a micro-regional level.

Route network density differs regionally (Fig. 11). Both in the Roman and early-medieval period the majority of routes appears to have been located in the eastern, northern and southern Pleistocene parts of the country. This is understandable since given their network friction these regions are more accessible than many of the Holocene areas. Clear exceptions are the western coastal dunes and the levees in the central-river area, both of which will have been travelled intensively in both periods.

Large-scale modelling of route networks is impossible without making certain assumptions regarding e.g. settlement locations, settled areas and most efficient paths. The NFM presented in this paper tries to limit the number of assumptions, and when needed only used archaeologically substantiated ones. The complex interaction between landscape and culture which form route networks requires high-resolution and large datasets. The assumptions made in route (or road) modelling should always be transparent and founded on solid data. We stress the importance of high-quality field data in archaeological modelling, route networks or otherwise, both for testing as well as defining variables. The available high-resolution, large-scale datasets in the Netherlands allowed us for the first time to model and validate route networks on a national scale.

7. Conclusion

In lowland regions such as the Netherlands in the past there existed a clear relationship between landscape factors and route orientation. Network friction focuses on the nature of this relationship by calculating local accessibility. The NFM presented in this study correctly models 88.7% of the known Roman and 86.4% of the known early-medieval infrastructure within a 1 km buffer and shows that transport obstacles and corridors exerted a strong influence on the spatial distribution of settlements, burial sites and shipping-related finds. Additionally, using the same buffers the NFM contains 81.7% of the known Roman and 72.2% of the known early-medieval isolated finds found in the Netherlands, suggesting these corridors to be frequent-travel zones. The implication is that network friction is a very useful tool to model the environmental framework for historical-route networks in low-elevated, geographically dynamic regions.

In AD 100 and 800 the number of routes in the western part of the Netherlands was clearly lower than in other parts of the country. This is understandable because in these parts network-friction values are generally lower and only a few movement corridors can be modelled. The presence of long-distance land routes in these regions will have been limited to the larger levees of the central river area and the western coastal dunes.

The NFM uses proven environmental and archaeological data to model past route networks and to validate its output. As such the model is evidence based. It is designed specifically for dynamic lowland regions. The NFM output may improve with the incorporation of more theoretical modelling on e.g. network analyses, road/route systems,

economic and religious activities. However the excellent results of the NFM suggest these approaches in itself to be insufficient to model route networks in low-elevated regions and a more integrated approach with landscape variables is required.

8. Outlook

This study can be regarded as the first archaeological effort towards large-scale lowland route modelling. The current NFM would benefit from a higher resolution. With the current datasets this is only possible by studying high-resolution micro-regions and incorporating these high-resolution data into the NFM. The data from these well-documented micro-regions would also show the full potential of the network-friction method.

Despite the fact that in our research area around at least 50% of the settlements are not (yet) known in the archaeological datasets, modelling results are promising. The minimum number/percentage of settlements required for the NFM to correctly model historical-route networks has not yet been determined. By arbitrarily removing settlements from the dataset, the minimum (data) requirements for the network-friction method can be determined.

The current NFM was specifically designed for the Netherlands. Network friction is applicable to dynamic lowland regions all around the world, especially in coastal areas. Application of the method in other areas will help to assess its full potential.

The current NFM allows for various future applications. First, the modelled route networks can be used to identify and locate spatial differences between the Roman and early-medieval periods: i.e. the long-term use of route networks. Since the NFM allows modelling landscape changes between periods, it would also be worthwhile to investigate the relationship between changes of the landscape and of route networks.

Second, although the current NFM has been developed as an explanatory model by increasing data resolution it can be adapted to function as a predictive archaeological model similar to the Indicative Map of Archaeological Values of the Netherlands (IKAW) (e.g. Deeben et al., 2002). Even with the current data resolution the high number of isolated finds located within the relatively small surface area of the route zones already strongly suggests that within these modelled zones the chance of finding undiscovered archaeology including infrastructural remains is relatively high.

Third, the current NFM could easily be adapted to model other time periods than the Roman period and Early Middle Ages. The method could be used to model prehistoric route networks and with small adaptations route networks post AD 800. The latter would however require the availability and selection of different datasets such as, amongst others, high-resolution reclamation data.

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Appendix A

Overview of settlements outside the calculated High Density Settlement Clusters (HDSC) which, based on archaeological or historical sources, can be regarded as central places:

A.1. Roman period

Overview of Roman central settlements based on archaeological and historical sources. Only those settlements were included with a clear central function (e.g. economy, political).

Name	Type	Source
Ulpia Noviamagus (Nijmegen)	Civitas capital	Hiddink, 1991
Forum Hadrianus (Voorburg)	Civitas capital	Hiddink, 1991
Aardenburg	Rural centre	Hiddink, 1991
Colijnsplaat	Rural centre	Hiddink, 1991
Cuijk	Rural centre	Hiddink, 1991
Elst	Rural centre	Hiddink, 1991
Halder	Rural centre	Hiddink, 1991
Ockenburg	Rural centre	Hiddink, 1991
Rijsbergen	Rural centre	Hiddink, 1991
Rossum	Rural centre	Hiddink, 1991
Valkenburg	Rural centre	Hiddink, 1991
Venlo	Rural centre	Hiddink, 1991
Wijchen	Rural centre	Hiddink, 1991
Katwijk-Brittenburg	Possible military site	Dhaeze, 2011
Katwijk-Uitwateringssluizen	Possible military site	Dhaeze, 2011
Den Haag-Scheveningseweg	Possible military site	Dhaeze, 2011
Den Haag-Ockenburg	Military (coast) site	Dhaeze, 2011
Voorburg	Fortified town	Dhaeze, 2011
Naaldwijk	Possible military site	Dhaeze, 2011
Naaldwijk-Hoogwerf	Possible military site	Dhaeze, 2011
Oostvoorne	Possible military site	Dhaeze, 2011
Goedereede-Oude Wereld	Possible military site	Dhaeze, 2011
Goedereede-Oude Oostdijk	Possible military site	Dhaeze, 2011
Westenschouwen-Roompot	Possible military site	Dhaeze, 2011
Oostkapelle-Oranjezon	Possible military site	Dhaeze, 2011
Colijnsplaat	Possible military site	Dhaeze, 2011
Aardeburg	Military (coast) site	Dhaeze, 2011
Brugge	Possible military site	Dhaeze, 2011
Oudeburg	Military (coast) site	Dhaeze, 2011
Maldegem-Vake	Military (coast) site	Dhaeze, 2011

A.2. Early-medieval period

Overview of early-medieval central settlements based on archaeological and historical sources. Only those settlements were included with a clear central function (e.g. economy, political).

Site	Type	Source
Deventer	Rural centre	Bosatlas 2011; Willemsen, 2014
Domburg	Rural centre	Bosatlas 2011; Willemsen, 2014
Wijk bij Duurstede/Dorestad	Rural centre	Bosatlas 2011; Willemsen, 2014
Medemblik	Rural centre	Bosatlas 2011; Willemsen, 2014
Nijmegen	Rural centre	Bosatlas 2011; Willemsen, 2014
Tiel	Rural centre	Bosatlas 2011; Willemsen, 2014
Utrecht	Rural centre	Bosatlas 2011; Willemsen, 2014
Witla (precise location unknown)	Rural centre	Bosatlas 2011; Willemsen, 2014

Appendix B

Overview of infrastructural subcategories in ARCHIS. Abbreviations used in ARCHIS are derived from the *Archeologisch Basis Register (ABR)* (Wiemer, 2002). ARCHIS code "IGEM" was not included into the model because this type of infrastructure postdates the Early Middle Ages.

Website: http://www.cultureelerfgoed.nl/sites/default/files/downloads/dossiers/abr_website2.pdf

ARCHIS (ABR) code	Description	Included in model
IBRU	Bridge	Yes
IDAM	Dam	Yes
IDIJ	Dike	Yes
IDUI	Culvert	Yes
IGEM	Pumping station	No

Appendix B (continued)

ARCHIS (ABR) code	Description	Included in model
IHAV	Harbour	Yes
IKAN	Canal	Yes
IPER	Parcel	Yes
ISLU	Sluice	Yes
ISTE	Jetty	Yes
IWV	Peat bridge	Yes
IWAT	Waterway (natural)	Yes
IWEG	(Unpaved) Road	Yes
IX	Undefined infrastructural find	Yes

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