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RESEARCH

Finding Vanished Routes: Applying a Multi-modelling Approach on Lost Route and Path Networks in the Veluwe Region, the Netherlands

Willem F. Vletter[*,†] and Rowin J. van Lanen[‡,§]

Route networks are influenced by cultural and environmental dynamics. Consequently, route networks themselves often are dynamic as well. This is especially true in lowland areas, such as the Netherlands, where environmental processes (e.g. geomorphological changes, floods) probably reshaped these networks numerous times. Many of the existing route networks in the Netherlands were established relatively recently, and little is known of their historical predecessors. Recent developments in spatial modelling may improve locating and analysing these old, vanished routes.

In this study we have applied two recently-developed applications for historical-route network modelling to the Veluwe (the Netherlands) in order to reconstruct the route network in the region around AD 1500. This region is not densely cultivated and is known to have a long history of routes and paths running through the landscape. The first method, network friction, uses high-resolution geoscientific and cultural data to calculate potential movement corridors and probable route zones. The second method uses a more traditional least-cost path (LCP) model based on surface, groundwater level and slope. The usefulness of these approaches for reconstructing past route networks and the general added value of these approaches was assessed by comparing the reconstructions to the few existing spatial overviews of historical-route networks in this region and hollow ways extracted from Airborne Laser Scanning (ALS) data.

Our findings show that the results of the first method, network-friction modelling, correspond best with the comparison data regarding known routes in the study area. However, the general results point towards the necessity of integrating the two applied methods, since a combination of these models best reflects the multiscale variability within regional route networks.

Keywords: Spatial modeling; routes; history; roads; paths; Airborne Laser Scan

1. Introduction

Route networks both reflect and influence (large-scale) cultural and landscape processes and therefore are key to understanding human-landscape interactions. Van Lanen et al. (2015a, 2015b) developed a new method for reconstructing large-scale (supraregional) route networks in the past. In this paper we investigate the applicability of this method and a more traditional least-cost path approach in order to improve our understanding of the layout of partly-vanished historical route networks on a regional scale. Locating vanished and abandoned routes is important because: (1) information about past routes derived from ALS data and historical sources probably only covers a small percentage of the once-existing networks and (2) route-network development can help to study human-landscape interactions in the past. Over time many routes will have disappeared mainly through dynamic geomorphological (e.g. erosion) and human-induced processes (e.g. agricultural and building activities). However, these same dynamics through route-network modelling enable us to calculate the probable location of many of these vanished routes, since not every region is equally suitable for travel and transport and therefore for hosting (persistent) route networks (Van Lanen et al., 2015a, 2016; Van Lanen, 2016).

Our study area is the Veluwe region in the Netherlands. The Veluwe is an area located in the central part of the Netherlands (ca. 1100 km^2; **Figure 1**). We selected this region as research area since high-resolution environmental (e.g. geomorphology, palaeogeography), cultural (e.g. settlement patterns) and Airborne Laser

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[*] Vienna Institute of Archaeological Science, University of Vienna, A-1190 Vienna, Franz-Klein Gasse 1, AT

[†] Groningen University, Department of Landscape History, Oude Boteringestraat 34, Groningen, NL

[‡] Utrecht University, Department of Physical Geography, Heidelberglaan 5, Utrecht, NL

[§] Cultural Heritage Agency of the Netherlands, Landscape Department, Smallepad 5, Amersfoort, NL

Corresponding author: Willem F. Vletter (willem.vletter@univie.ac.at)

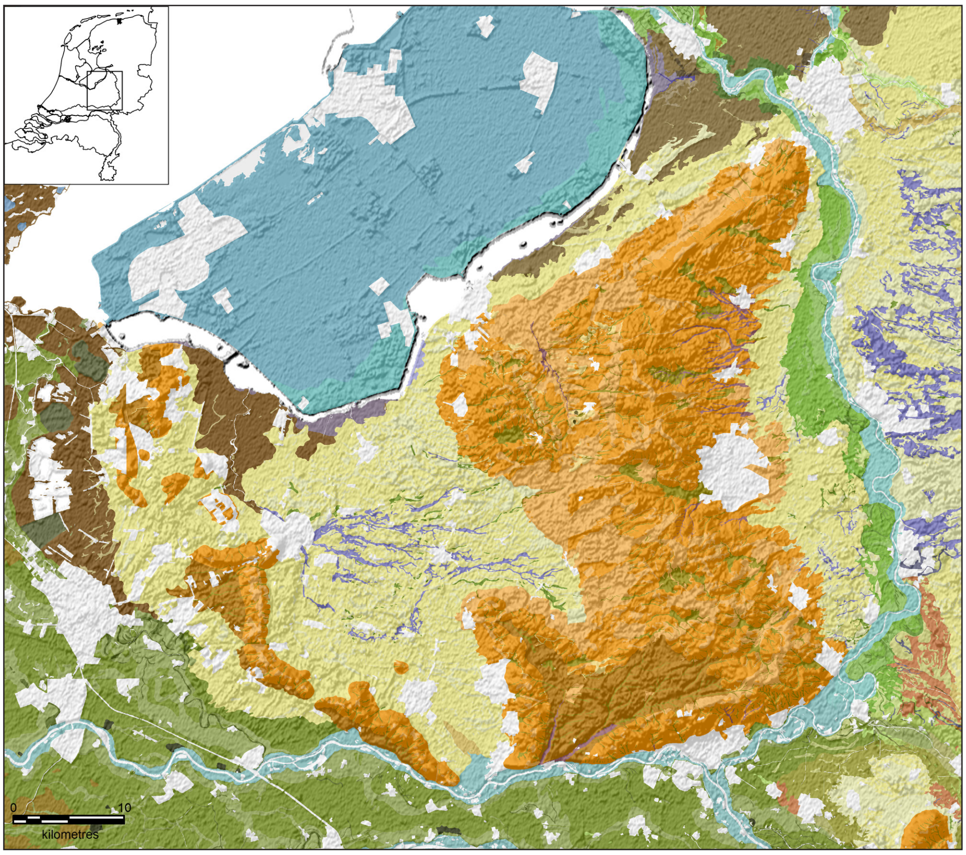

Figure 1: Section of the archaeological landscape map of the Netherlands (1:50,000) depicting the Veluwe region. Clearly visible are the characterizing high push moraines in this area (light and dark orange sections). For a detailed description of the individual landscape units, legend and background information please see Rensink et al. (2017).

Scanning (ALS) data are available, making this region well suited for a more detailed, integrated modelling approach (**Figure 2**). The region features many different landscapes including large sand drifts, woodlands and heaths. The most striking characteristic of the Veluwe is the presence of relatively high ice-pushed moraines formed during the Saalian (ca. 150,000 years ago). Additionally the Veluwe contains some very long cover-sand ridges and snowmelt water valleys. Relief in the region nowhere exceeds 110 meters (the highest point of the push moraines) and slopes are generally gradual.

It has been suggested that some of the routes on the Veluwe date back as far as the Bronze Age (2000–800 BC) and possibly are marked by prehistoric barrows (Bakker, 1976). Using visibility analyses and geographical information systems (GIS), Bourgeois (2013) underlines that these mounds might have been used as landmarks for routes, but also notes that convincing physical evidence for these routes is lacking. The earliest confirmed remnants of routes within the research area date to the late Middle Ages.

Route-network modelling is essentially a type of spatial modelling. Recently Van Lanen et al. (2015a) developed a network-friction model (NFM) in order to reconstruct Roman and early-medieval route networks. Following the definition by Van Lanen et al., "network friction is the variable that determines potential regional accessibility based on the comparison of local and surrounding landscape factors" (2015a, 200–201). This model was specifically designed to model landscape prerequisites for Roman and early-medieval route zones in dynamic lowlands where relief is often not a decisive factor for route or path orientation. By integrating cultural (e.g. settlements, burial sites) and environmental (e.g. palaeogeography, geomorphology) factors in the NFM, Van Lanen et al. (2015b) modelled possible route zones on a supraregional level for the present-day Netherlands (Appendix A). The models' outcome was validated against archaeological data on infrastructure and isolated finds and obtained good results. However, the calculated NFM-route zones were modelled using a relatively straightforward efficient path computation, i.e. the shortest distance between two settlements following the most accessible areas (Van Lanen et al., 2015b). As was already stated by Van Lanen et al. (2015a, p. 214, 2015b, p. 156), the next necessary steps for the network-friction method are to: 1) test its applicability on a more detailed regional level and for a different historical period and 2) to compare the models' outcome with results from other route-network reconstruction methods, such as the extraction of roads and paths from ALS data, and the study of historically attested routes.

In this paper we apply two different types of route-network modelling: the network-friction method and the more traditional LCP calculations. The aims of this paper are: 1) to reconstruct route networks around AD 1500 by

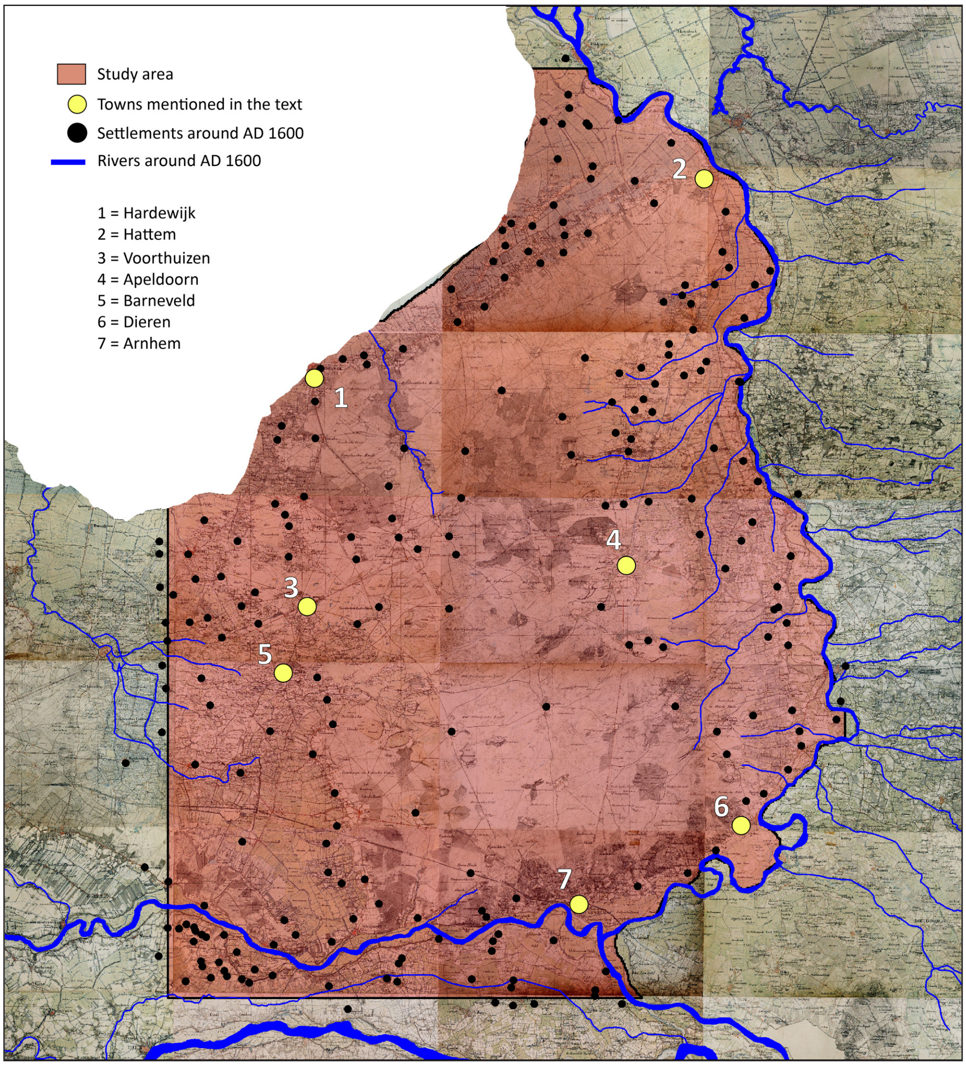

Figure 2: The research area (in red) including settlements overlaid on the Topographic Military Map 1850 (TMK 1850). Contemporary rivers are visible in blue.

applying both modelling techniques on the research area; 2) to determine the general applicability and usefulness of both approaches for route-network reconstructions on a regional scale level by comparing each outcome with data on known historical routes in the study area.

2. Route networks and GIS modelling

Over the last few decades a substantial number of papers and books have been written about spatial and predictive modelling in archaeology. Many of these primarily are theoretical exercises of exploring (technological) possibilities (e.g. Van Leusen et al., 2005; Jiang and Eastman, 2000; Murietta-Flores, 2010). Moreover, many of these studies generally have produced few results or have had relatively limited impact (e.g. Gietl et al., 2008; Verhagen, 2013; Polla and Verhagen, 2014). One of the approaches we are going to apply, LCP, can be defined as a predictive model. We define the latter as a method predicting routes or paths between two specific locations. The NFM is much more a spatial model. Although the NFM calculates potential movement corridors for probable routes based on multiple geoscientific variables, in itself it does not predict routes or paths. The NFM however does allow for the integration of large-scale archaeological data and the calculation of supraregional route zones (Van Lanen et al., 2015b). Assuming that all spatial and predictive models are "expressions of a probabilistic relationship between human behaviour and prior existing spatial conditions" (Whitley, 2005, 124), the outcomes of the NFM and LCP models can be compared.

Traditionally, LCP calculations are most common in route-network modelling. By calculating so-called friction surfaces this method calculates the most probable routes by determining which path requires the least effort to move between two points. In most cases, these friction surfaces are mainly based on the slope of the terrain. However, slope generally has not been the single decisive factor in past movement through the landscape (Howey, 2011). Alternatively, optimal-path calculations are used to better understand the formative principles of routes and paths and to compare these to historically documented routes (Posluschny and Herzog, 2011; Doneus, 2013). Other less-frequently applied route-network modelling techniques include circuit modelling (Howey, 2011) and *From Everywhere To Everywhere* (*FETE*) (White and Barber, 2012). Often these route-network modelling techniques neglect the influence of non-environmental factors (e.g. political, socio-economical, religious) which probably greatly influenced past route-network development (Bell and Lock, 2000; Llobera, 2000; Van Lanen et al., 2015b). Other studies point at the relative importance of other cost factors such as river crossings and different types of transport (e.g. by foot or carriage) in the formation of these past routes (Herzog, 2013). Van Lanen et al. (2015a, 2015b) suggest that in dynamic lowlands relief probably was not a decisive factor for route orientation, and that combined local and surrounding landscape conditions (e.g. soil types, groundwater levels) were much more decisive. Current models often are not adapted to include all these different decision-making factors (Citter, 2012). For this reason a variety of different and complementary models is needed to reconstruct historical reality (Verhagen and Whitley, 2012; Citter, 2012; Herzog, 2013; Fovet and Zakšek, 2014).

Despite the difficulty of incorporating cultural and environmental variables, predictive and spatial modelling in GIS are very promising techniques for the discovery and analysis of prehistoric and historic route and path networks. This is especially true for map-based reconstructions, because the chronology and status of known routes may be uncertain and many major connections have not yet been identified. Routes have history, and their course results from a long and complex evolution combining abandonments, changes in status and reactivations. Optimal path modelling simulating the connections between contemporary archaeological sites helps to comprehend the chronology and hierarchy of former communication networks (Fovet and Zakšek, 2014).

Past routes in our research area almost always were unpaved, implying that tracks may have wandered within route zones following broad movement corridors often several hundred metres wide. We define movement corridors as those areas where landscape setting provides people with favourable connectivity options, e.g. route zones, to other places of interests, such as settlements, fortresses, mining areas (cf. Van Lanen and Pierik, 2017; Van Lanen, 2017). These route zones filled with (seasonally) shifting tracks reflect generalized routes and should not be regarded as exact constants (Bell and Lock, 2000; Van Lanen et al., 2015b). As such, these route zones are spatially more dynamic than roads (which are much more fixed features connecting two places), but in orientation they are very similar (Van Lanen et al., 2016). Because of this flexibility, cultural and environmental factors play a decisive role in the formation of route zones. Therefore in order to accurately model these complex networks, spatial models integrating both cultural and environmental dynamics should be produced for specific cultural periods (Wilcox, 2009; Van Leusen et al., 2005).

3. Material

NFM modelling in the current study was based on the datasets used by Van Lanen et al. (2015a, 2015b; Sections 3.1–3.4). LCP modelling was based on Airborne Laser Scan (ALS) data and groundwater-level reconstructions extracted from the soil maps (Sections 3.5–3.6).

3.1. Palaeogeography AD 1500

Palaeogeographical reconstructions for multiple periods were first issued in 2011 with the presentation of the Atlas of the Holocene Netherlands (Vos et al., 2011). These maps were updated in 2013 when a second generation became available (Vos and De Vries, 2013; Vos, 2015). The palaeographical reconstructions by Vos et al. (2011, 2013) and Vos (2015) describe the genesis of the Dutch landscape over the last 11,000 years. The reconstructions are multi-disciplinary in origin, combining numerous datasets from the Humanities and Geosciences, e.g. archaeology, geology, palaeoecology, onomastics and soil sciences. Therefore these maps can be used as a nationwide reconstruction of the palaeolandscape for both Holocene and Pleistocene areas.

3.2. Geomorphology

A nationwide, digital geomorphological map became available in 2003 (Koomen and Exaltus, 2003; Koomen and Maas, 2004). The map was created by combining field observations, bore-hole data and surveys with detailed elevation models (Koomen and Maas, 2004). The dataset not only contains information on the individual geomorphological units, but also on relief, genesis and ages of the landscape elements on a 1:50,000 scale. Therefore the map greatly adds to our understanding of the past landscape, especially regarding the higher, more stable Pleistocene regions. As a result, the geomorphological map of the Netherlands has proven itself invaluable for archaeological predictive modelling and was used amongst others for the indicative map of archaeological values (IKAW) (Van Leusen et al., 2005; Deeben, 2008).

3.3. Soil and groundwater level data

The soil map of the Netherlands has been developed based on the soil-classification system of De Bakker and Schelling (1989). It provides an overview of all current soil types (up to a depth of 1.20 metres) in the Netherlands (Steur and Heijink, 1991; De Vries et al., 2003). Additionally, the datasets also contain data on the average groundwater levels between 1958 and 1999 (De Vries et al., 2003; Van de Gaast et al., 2010). In contrast to the geomorphological dataset, the soil map does not provide any chronological information about the ages of individual soils. Since soils change through time, the use of the soil map for historical periods requires expert judgement. This map is especially useful for the analyses of higher, more stable regions in the Netherlands, such as the Veluwe.

3.4. Settlement data

Settlement data for the Veluwe region were collected by using *OpenStreetMap* data on current places in the Netherlands.[1] Rutte and IJsselstijn (2014) claim that most towns in the current Netherlands date back to before AD 1300. Therefore present-day data can be used to recreate 16th-century habitation and to determine route-network persistence (Van Lanen et al., 2016). Maps from part 1 and

2 of the *Atlas van Nederland* (1984) made by Prof. dr. Renes, Histland[2] data and the Archaeological Landscapes Map of the Netherlands[3], were used to filter out settlements located in uncultivated lands (e.g. heathlands, younger reclamation areas) during the 16th century.

3.5. Historical roads in the Veluwe region

Historical road data for the Veluwe region were extracted from the AD 1600 route reconstructions by Horsten (2005) and the Topographic Military Maps 1850 (TMK 1850). Horsten (2005) reconstructed historical road networks for the period between the 16th and 19th century. This historical road atlas is primarily based on old maps, and reconstructs major interregional roads for the years ca. AD 1600, ca. 1800 and ca. 1848. Horsten (2005) choose these intervals since no detailed old maps are available dating before AD 1600, and after AD 1848 railway networks substituted many of these thoroughfares (Horsten, 2005). In the current study we used the earliest AD 1600 reconstruction for validation purposes (**Figure 3**).

The TMK 1850 first appeared between 1850 and 1864 (Van der Linden, 1973). The map constitutes the oldest nationwide map of the Netherlands on a 1:50,000 scale and was compiled for military purposes. Through thematic colouring the TMK 1850 provides a high-resolution overview of the mid-19th-century landscape. Since the map predates the massive industrialisation that began at the start of the 20th century, which radically changed many parts of the Dutch landscape, it provides invaluable information on past routes and other historical landscape elements that have since disappeared. Although also older, local maps are available, for example for the current province of Gelderland, these maps lack sufficient geographical precision to be used for this study.

3.6. Airborne Laser Scanning (ALS) data

In the Netherlands ALS data are the basis of the digital elevation model of the Netherlands, which is referred to as AHN. In 2003 the first generation of this model, the AHN-1, became available. This model uses a density of one height measurement per 1 to 16 m^2, resulting in a highest available grid-cell resolution of 5 m^2 (Brand et al., 2003; Swart, 2010). This raster is too crude for detailed analyses, which limits the usefulness of the AHN-1 on a local scale. To counter these limits a second generation of the AHN, the AHN-2, was presented in 2013 (Van der Zon, 2013).

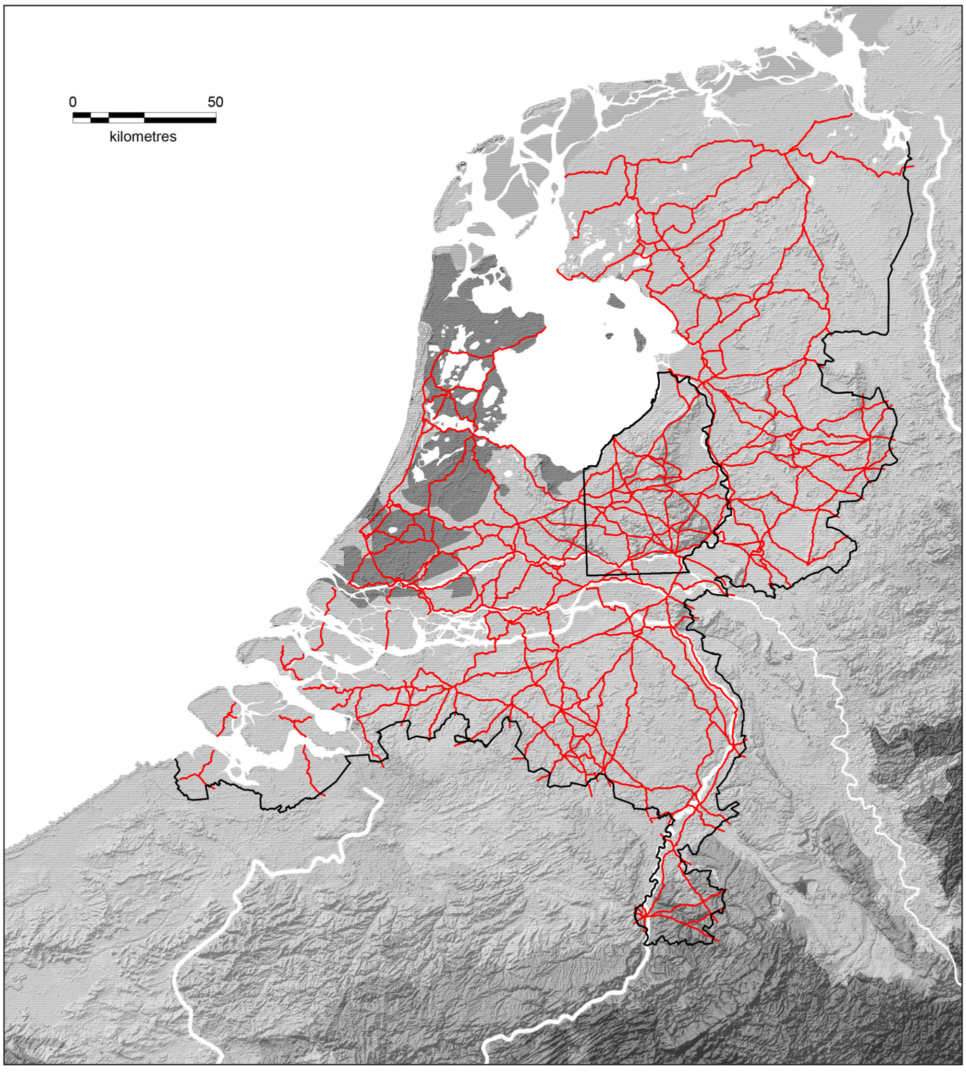

Figure 3: Road network in the Netherlands around AD 1600 reconstructed by Horsten (2005). In the present study only connection routes on the Veluwe (smaller framework) were included.

Table 1: ALS parameters used for route-network modelling.

Meta-information ALS	
ALS-Project	Actueel Hoogtebestand
Purpose of Scan	Water management
Time of Data Acquisition	April 2010
Point-distribution (pt. per sq. m)	6–10
Scanner Type	Riegl LMS-Q680i Full-Waveform
Scan Angle (whole FOV)	45°
Flying Height above Ground	600 m
Speed of Aircraft (TAS)	36 m/s
Laser Pulse Rate	100 000 Hz
Scan Rate	66 000 Hz
Strip Adjustment	Yes
Filtering	Yes
DTM-resolution	0.5 m
Interpolation method	Moving planes

The new dataset contains up-to-date measurements and a much higher resolution, with 6–10 measurements per m^2. For the sake of clarity, we use the (raw) ALS dataset and not the AHN models based on it. We defined the most important parameters of the ALS data for our route-network modelling in **Table 1**.

4. Method

The presented datasets were used to create a NFM showing local accessibility and to reconstruct route zones in the study area based on the network-friction method and LCP modelling.

4.1. The network-friction model (NFM)

The Veluwe NFM is based on the method presented by Van Lanen et al. (2015a; see Appendix A for more background information). It excludes data postdating AD 1600 and exclusively uses a 100 × 100 m grid-cell resolution. The new model integrates environmental data in order to locate landscape obstacles that could limit accessibility (Sections 3.1–3.3). It covers the Veluwe region and immediate surroundings (**Figure 2**). It is important to include the latter since habitation in this area is largely clustered on the edges of the Veluwe. The model consists of 250,447 individual grid cells, roughly covering a region from the current city of Amersfoort in the west to the river IJssel in the east. Contrary to the NFM developed by Van Lanen et al. (2015a) which used a 500 × 500 m grid-cell resolution, the Veluwe NFM consists out of 100 × 100 m grid cells. Each cell was given a unique identifier and location coordinates. The Veluwe NFM consists of 14 data fields, covering all imported datasets (Sections 3.1–3.4 and **Table 2**). Point-location data such as settlements were not converted to the grid.

Table 2: Model design of the Veluwe network-friction model.

Field name	**Description**
Grid_ID	Unique identifier for each individual grid cell
Grid_ID500 m	Unique identifier grid cell in larger nationwide grid
Unit_AD1500	Unit of grid cell according to palaeogeographic map of AD 1500
Acc_AD1500_LA	Accessibility AD 1500 based on land factors
Unit_Arch_La	Unit of grid cell according to geomorphological map of the Netherlands
Arch_LA_GeomorfCode	Original geomorphological code map of the Netherlands
Acc_Arch_La_LA	Accessibility geomorphology based on land factors
Unit_Soil	Unit of grid cell according to soil map of the Netherlands
Code_soil	Original code from soil map
Acc_Soil_LA	Accessibility based on land-factors soil map
Unit_GW	Original code groundwater level map
Acc_GW	Accessibility based on groundwater reconstructions
Nf_AD1500_Sum	Combined network friction sum AD 1500
Nf_AD1500_AvG	Combined network friction average AD 1500

The Veluwe NFM is designed to reconstruct local accessibility, which is crucial for route orientation. Since within the NFM each grid cell can contain only one specific data unit per imported dataset (e.g. palaeogeography, geomorphology), based on archaeological and historical datasets we first imported traditionally accessible landscape units (e.g. high, dry areas; Appendix A). As a result, the NFM represents the maximum amount of possible movement corridors. In line with Van Lanen et al. (2015a) data was imported by overlaying the geoscientific datasets on the grid. The geometric intersections were imported using the following query in MapInfo 12.0.2:

Grid_ID.obj intersects Unit_External_Dataset_X.obj

In this SQL-query the location geometry (.obj) of each grid cell (Grid_ID) is compared to a specific landscape unit (e.g. peat, ice-pushed ridge) from each of the external datasets (Section 3). Grid cells intersecting these selected geoscientific polygons were then updated with the content of the external dataset. This import process was repeated for each of the geoscientific datasets. Next, within the geoscientific datasets accessibility values were given to each landscape unit following the classifications presented and substantiated

Table 3: Network-friction levels as defined by Van Lanen et al. (2015a).

Description	Network-friction value
Inaccessible	1
Poorly accessible	2
Moderately accessible	3
Reasonably accessible	4
Accessible	5

in Van Lanen et al. (2015a; Appendix A). These values were then used to calculate network-friction averages depicting local accessibility based on natural landscape settings showing obstacles and corridors for movement in the region (**Table 2**; Appendix A). Local accessibility was defined using five network-friction levels: 1–5, ranging from inaccessible to accessible respectively (**Table 3**).

4.2. Modelling route zones based on network friction

NFM-route zones were modelled based on the Veluwe NFM and available settlement data (Section 3.4). Deviating from the original method by Van Lanen et al. (2015b; Appendix A) we only modelled land routes for the research area since no detailed overviews of water routes for the period around AD 1500 exist. Additionally, we excluded burial sites from our model, since the location rules surrounding these areas completely differ from the Roman and early-medieval periods. NFM-route zones reflect probable zones where people in the past frequently moved through the landscape, i.e. areas likely to contain roads, routes, paths and tracks. These route zones were modelled based on the assumption that they are largely defined by the wish to follow movement corridors (pull factors) and consequently to avoid movement obstacles (push factors). Following this hypothesis the shortest distance between two settlements following the best possible networks-friction values was calculated. These calculated lines were then converted to route zones with a width of 100 m (i.e. the highest possible accuracy level in a 100 × 100 m grid-cell resolution), which were used to compare with data on extracted hollow ways and known AD 1600 routes.

4.3. LCP model

In order to determine the applicability of the LCP method we selected four well-known historical roads running through the study area: 1) the *hessenweg* between Hattem and Voorthuizen, connecting Amsterdam over land to Germany, 2) the road between Arnhem and Harderwijk (*Harderwijkerweg*), 3) the route from Dieren to Barneveld and 4) the route between Apeldoorn and Voorthuizen.

Since in relative lowlands such as the Netherlands slope often is not a decisive factor (Verhagen, 2013) (Section 2), we have applied an LCP model incorporating three factors: terrain, slope and groundwater levels. Terrain values were based on two factors: the vicinity to water bodies and depressions in the landscape. We calculated the vicinity to water bodies by applying a threshold in the digital-terrain model (DTM) of the Veluwe based mainly on the largest water body in the region, the *Zuiderzee* (now IJsselmeer). Nevertheless, other water bodies like creeks were also taken into account when setting the threshold. Depressions in the landscape were also identified based on the DTM in combination with the suited tools in ArcGIS (fill and cut fill). These values were then combined into one GIS layer reflecting the lower, wetter areas. All remaining areas were classified as higher grounds. In order to make them suitable for LCP modelling in ArcGIS, the values (costs) of two classes were based on the terrain coefficients of Soule and Goldman (1972).

In our LCP calculations, terrain, slope and groundwater levels have (changeable) weight values, which serve as input for the cost-path calculation tool in ArcGIS. This allows us to calculate LCP routes between two places and to compare these trajectories with data on historical routes. In order to optimize the comparison with the NFM-route zones we selected routes that cross the study area in different directions.

4.4. ALS extraction

Remnants of cart tracks and hollow ways were extracted using ALS data from the Veluwe. Based on the extraction model developed by Vletter (2014) a semi-automatic extraction was executed on the data from the Veluwe (Section 3.6). The micro topography was visualized in grey scales using the *openness* module in OPALS developed by the Technical University of Vienna (Yokoyama et al., 2002; Pfeifer et al., 2014). Although some visualization techniques might provide better results for the reconstruction of microrelief in flat areas (Hesse, 2016), we chose for *openness* because other techniques are less suited for extraction purposes. We used openness in an extraction model created in the software plug-in Feature Analyst (FA) in ArcGIS. The original extraction model for the Leitha area was adjusted to fit the conditions of the research area. Since it is difficult to differentiate between man-made linear features, such as (historical) roads and paths made by cart and wagons, and natural linear features, some additional manual mapping based on expert judgement was needed. Further, the merge and dissolve tools in ArcGIS were used to create road sections. In order to allow a comparison between these ALS-extracted hollow ways (which can spread over hundreds of meters) and our NFM and LCP routes, we drew a 'centre line' through the extracted zones.

4.5. Modelling validation through comparison data

In order to determine the applicability and usefulness of the Veluwe NFM and LCP models we compared the modelling outcomes with several other datasets on route networks in our study area. First, the NFM and LCP outcomes were compared with data on known routes in the study area through a comparison with the TMK 1850, the AD 1600 route network compiled by Horsten (2005), and the extracted ALS route data. Second, we used the NFM to calculate the correspondence between local accessibility values based on landscape setting and the LCP model, routes visible on the TMK 1850, the AD 1600 route network, and extracted ALS route data.

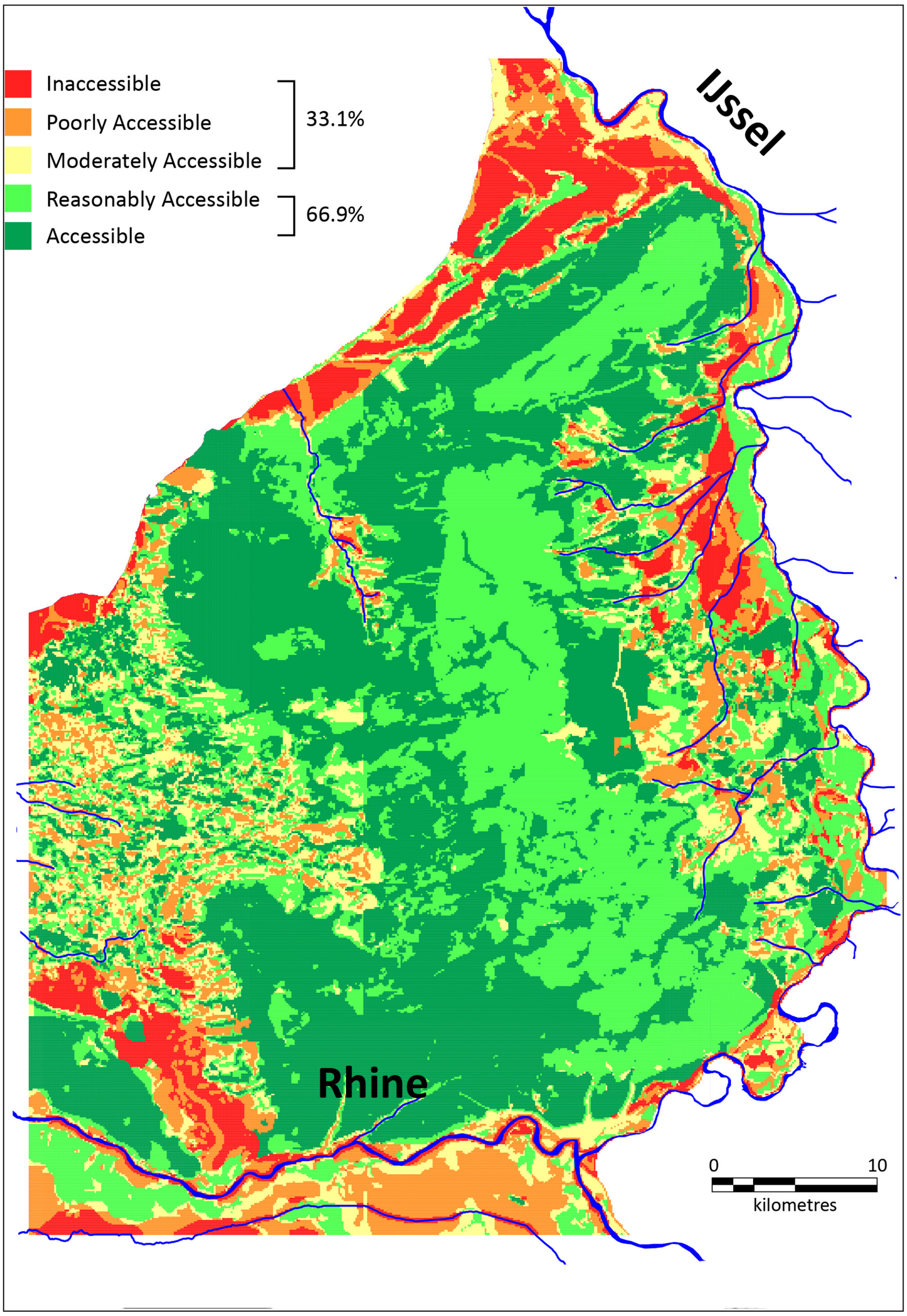

Figure 4: Network-friction map of the research area around AD 1500. Probable movement corridors are show dark green, and obstacles in red. Additional percentages of poorly and well-accessible areas are given. Major rivers (in blue) bordering the research area, the river IJssel in the east and the river Rhine to south.

5. Results

5.1. Network-friction map Veluwe ca. AD 1500

Based on the network-friction values the research area is divided into several corridors and obstacles for movement (**Figure 4**). The central part of the Veluwe appears to have been relatively well accessible. This is in contrast to the eastern and southern parts, where the rivers Rhine and IJssel (and their floodplains) constituted clear obstacles. In these parts the location of bridges and ferries must have determined the orientation of routes. Several stream valleys ran from the central part of the Veluwe to the edges of the research area. In the lower parts of these valleys the occurrence of peat and clay severely must have hampered movement, especially in the western part of the research area (**Figure 4**). Accessibility in the north of the research area was negatively influenced by a large peat area and the water from the *Zuiderzee*.

5.2. NFM route zones

Route zones were modelled using settlement distribution around AD 1600 and the method presented by Van Lanen et al. (2015b; Appendix A) (**Figure 5**). Results show that the majority of the modelled route zones are located in the western part of the research area. Only a few routes

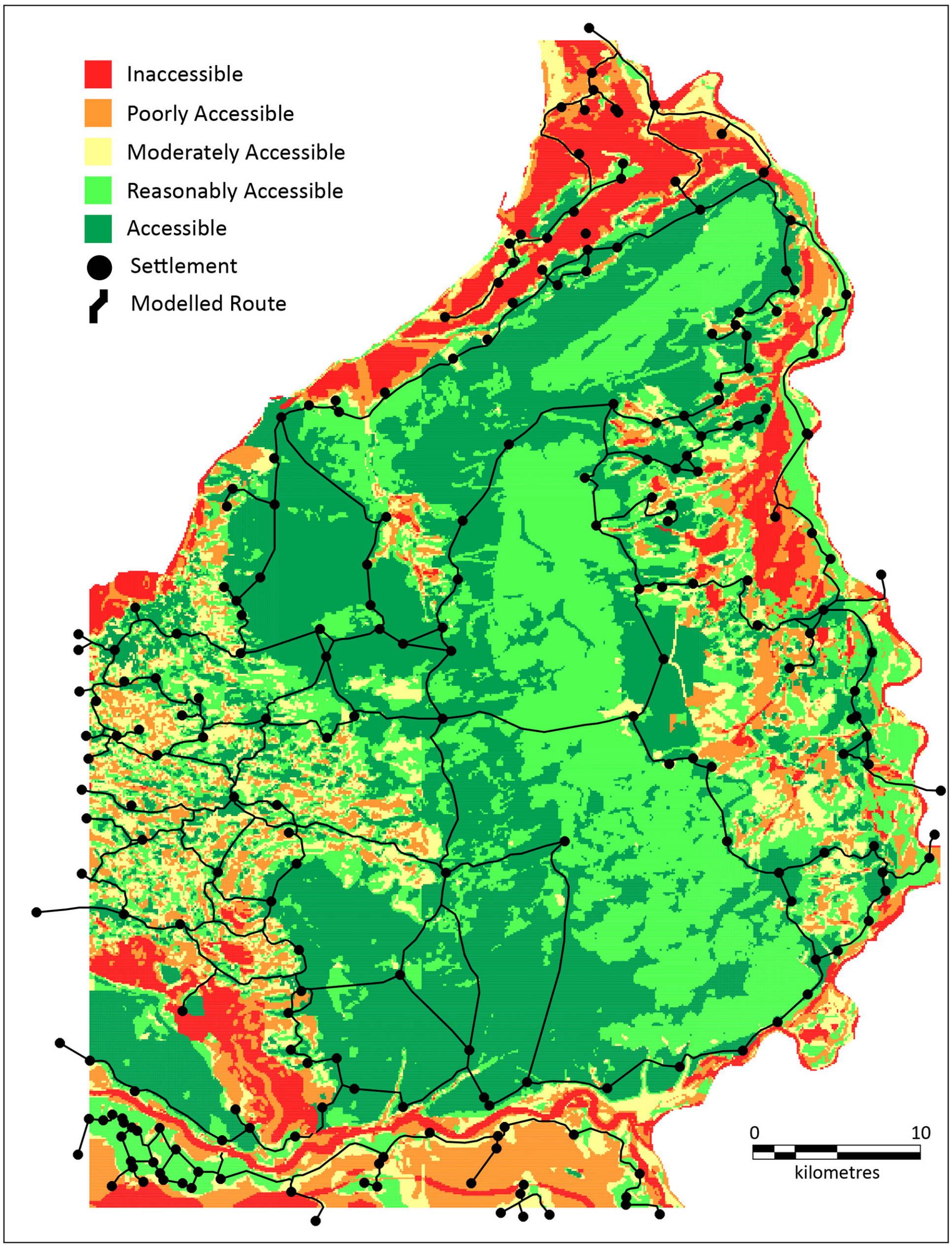

Figure 5: Route network based on the network-friction approach in the Veluwe area around AD 1500.

connected settlements east and west from the higher push moraine, which seems to have formed an obstacle. Route zones in the western and eastern parts of the study area clearly were influenced by local soil conditions such as the presence of peat and by the vicinity of waterways (**Figure 5**).

5.3. LCP routes

Based on the LCP model we were able to calculate 4 LCP routes (**Figure 6**). The modelled routes point towards an especially strong influence of the terrain factor on route-network orientation. In general, groundwater levels and slope appear to have been of less influence. The LCP route between Arnhem and Harderwijk (*Harderwijkerweg*) is an exception, since here multiple groundwater-level differences influenced route orientation. The factor slope appears to have been least influential on the routes in the area. Therefore, the LCP model allows us to calculate routes and to determine the relative influence of specific landscape factors on route-network development. The flexibility of the model, i.e. the possibility of assigning different or new weight values to individual factors, allows us to easily expand or change the focus of the model.

5.4. ALS-extracted routes

Based on the ALS extraction we were able to locate a high number of hollow ways (**Figure 7**). Primarily these could be extracted for the sandy regions, with the exception of the sand-blown areas where past roads and paths probably are covered. The western and eastern parts of the study area show limited signs of hollow ways, which is probably due to different soil conditions (mainly peat and clay) in these parts. Looking at the directionality of the extracted hollow ways, they can be divided into two main groups: 1) a high number of west-east connections crossing the push moraine; 2) a lower number of north-south connections

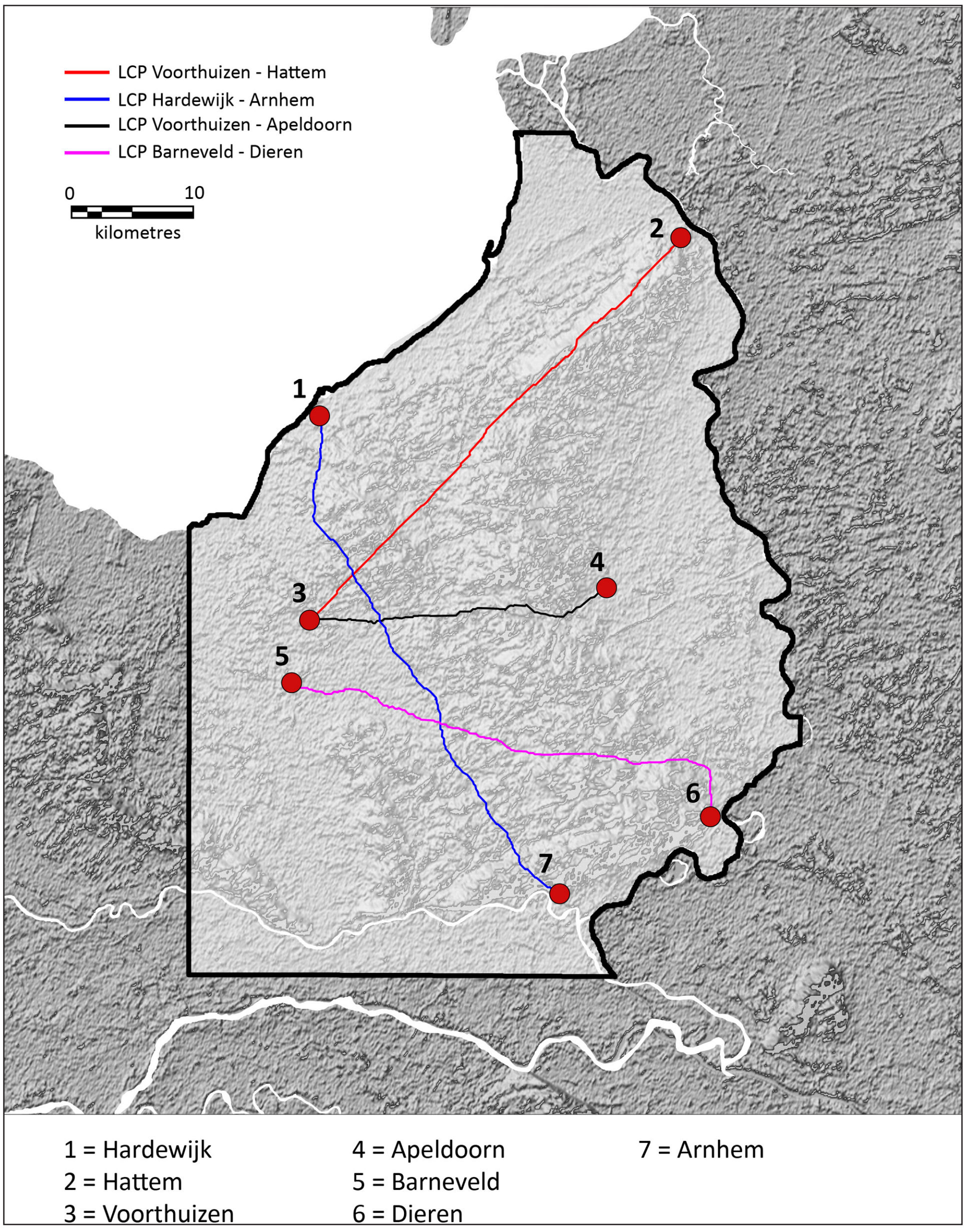

Figure 6: Least-cost path (LCP) calculated routes on the Veluwe. Four routes were preselected and modelled: 1) the LCP running from Voorthuizen to Hattem, 2) LCP running from Harderwijk to Arnhem, 3) LCP running from Voorthuizen to Apeldoorn and 4) the LCP running between Barneveld and Dieren.

descending from the push moraine to the coastal plane, especially in the northern part of the study area.

6. Validation through comparison data

In order to determine the applicability of the NFM and LCP models we compared the outcomes with existing route-network datasets pertaining to the study area. As comparison data we used the ALS-extracted hollow ways, routes visible on the TMK 1850, and the AD 1600 route reconstruction by Horsten (2005).

6.1. Validating the NFM

6.1.1. NFM accessibility

In order to determine the usefulness of NFM accessibility calculations, we computed the agreement between the ALS-extracted hollow ways, the AD 1600 route network and the TMK 1850 routes (**Table 4**). For the comparison datasets we determined the absolute number (in metres/grid cells) and the surface percentages of routes located within either well-accessible or poorly-accessible areas (NFM values 4–5 and 1–3, respectively). For each of the comparison datasets a convincing agreement between local accessibility and the occurrence of routes can be identified, showing that a combined landscape setting clearly influences route-network development (**Table 4**). The relative high number of ALS-extracted hollow ways located in well-accessible areas (99.0%) is best explained by preservation circumstances, i.e. the hollow ways that still remain today are best preserved in higher and dryer areas, which often also reflect the well-accessible movement corridors. For the AD 1600 network, some routes ran through less-accessible areas, mainly near the rivers in the south and northeast of the study area (**Figure 7**). Although the lowest agreement of the TMK-

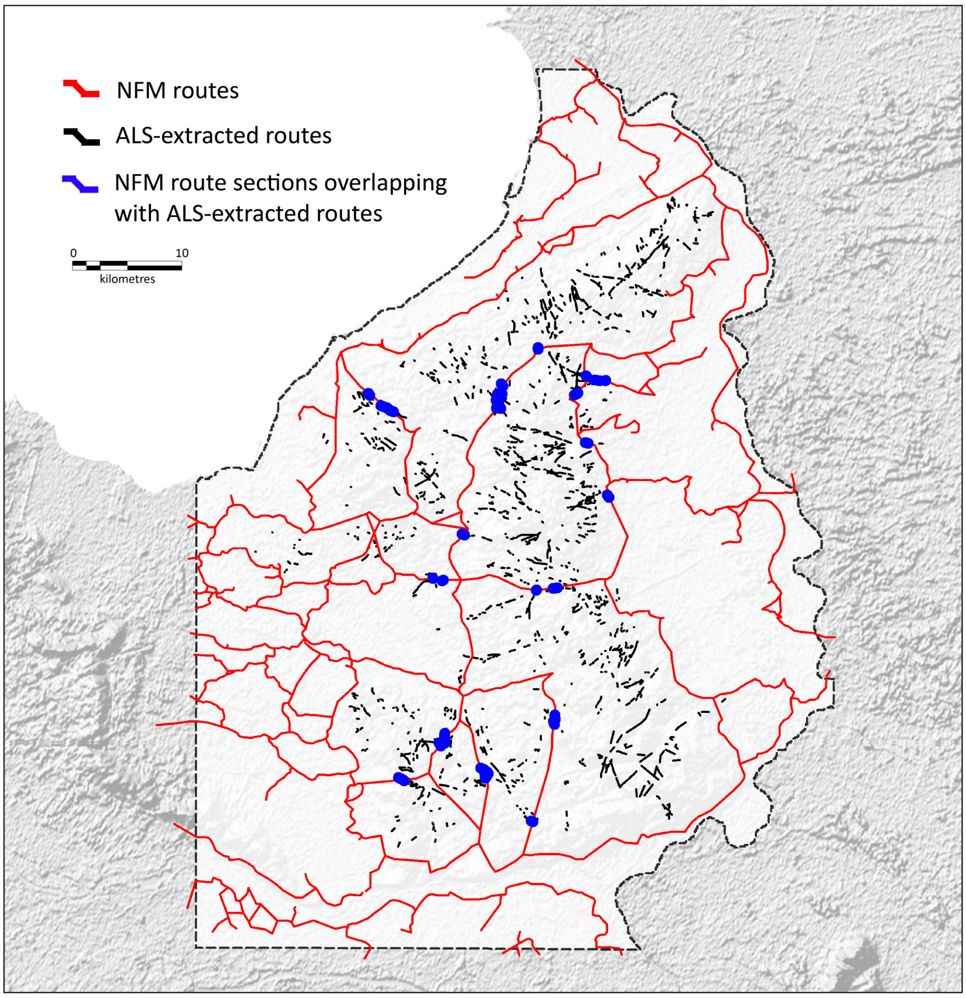

Figure 7: Hollow ways (in black) extracted from airborne laser scanner data. Sections where these hollow ways correspond with the calculated NFM-route zones (red) are highlighted in blue.

Table 4: Agreement between local accessibility based on network friction, the ALS-extracted hollow ways and the AD 1600 route network.

Description	**NFM value <= 3**	**NFM value >= 3**	**% NFM value <= 3**	**% NFM value >= 3**
ALS-extracted hollow ways (in metres)	234	269247	1.0%	99.0%
AD 1600 route network (in square metres)	1397	6283	18.2%	81.8%
TMK-1850 routes (n grid cells)	35359	117061	23.2%	76.8%

1850 routes, being still quite high at 76.8%, ran through well-accessible areas, it should be noted that in the entire NFM 66.9% of the grid cells reflect well-accessible areas (n = 167,494).

6.1.2. NFM-route zones

The calculated NFM-route zones (100 m wide) were compared with the ALS-extracted hollow ways, the AD 1600 route network, and routes shown on the TMK 1850 (**Table 5**). For each of the comparison datasets we determined the surface area of routes corresponding with the NFM-route zones. Results show that only 2.3% of the ALS-extracted hollow ways are located in NFM-route zones (**Figure 8**). This might be explained by the fact that hollow ways reflect a different chronological time frame or a different type of connection (i.e. more local paths within the network). A strong argument for this interpretation is the perpendicular orientation of the NFM-route zones and the ALS-extracted hollow ways. Agreement with the AD 1600 network is notably higher: 29.2% (**Table 5**; **Figure 9**). Looking at the distribution of the overlap between the two networks, agreement in the lower parts of the study area is relatively high, predominantly the western part. Additionally, the

Table 5: Agreement between route zones (100 m wide) based on settlement data and network friction, and the ALS-extracted hollow ways, the AD 1600 route network and the TMK 1850.

Description	No agreement with route zone (in km^2)	Agreement with route zone (in km^2)	% Not correlating with route zone	% Correlating with route zones
ALS-extracted hollow ways (in km^2)	1570	37	97.6%	2.4%
AD 1600 route network (in km^2)	44.8	18.5	70.8%	29.2%
TMK 1850 routes (in km)	782.2	313.2	60.0%	40.0%

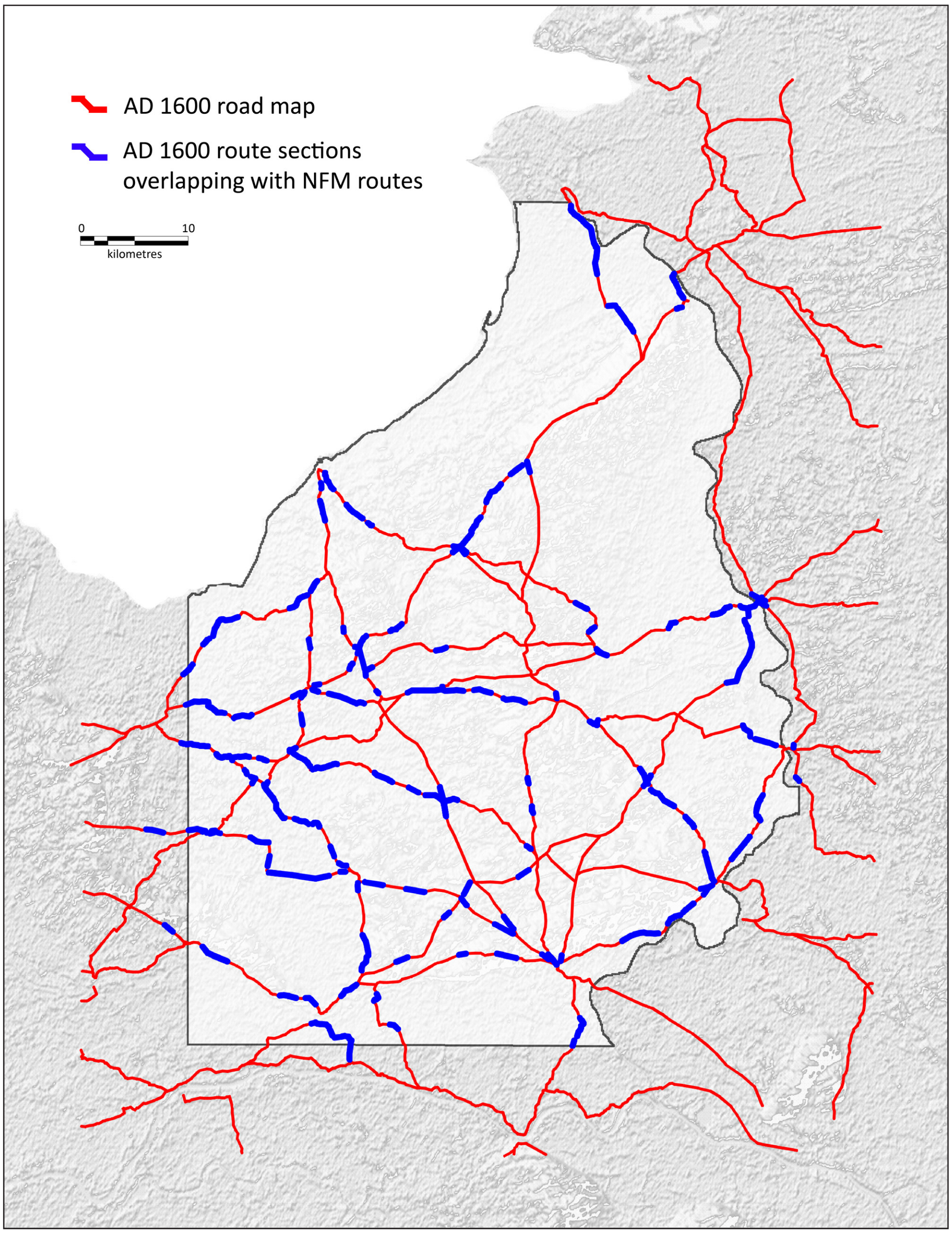

Figure 8: AD 1600 road-map sections overlapping with NFM routes (in blue).

dissemination of the overlapping route sections visually points towards a higher agreement when increasing route-zone width, i.e. correlating route sections covering the majority of the network (**Figure 9**). The largest deviation between the two networks appears to be located on top of the largest push moraine in the area. Here the NFM fails to reconstruct the thoroughfare reconstructed by Horsten (2005) running on top of

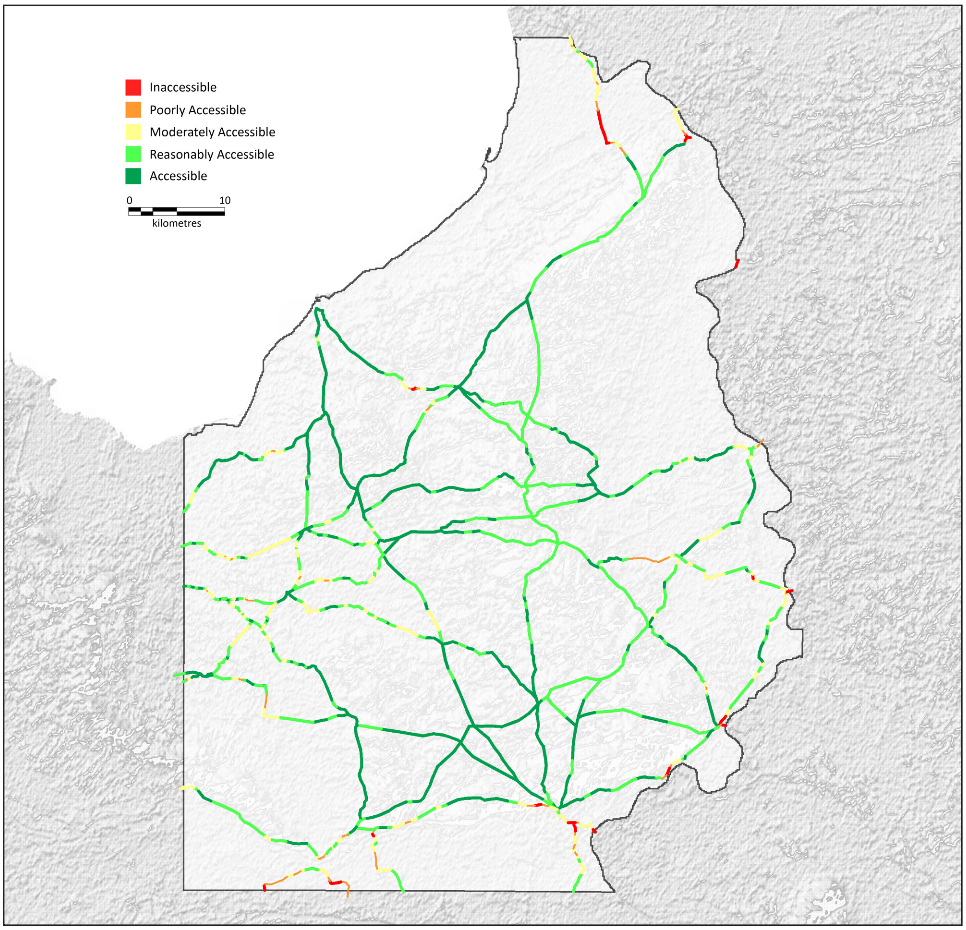

Figure 9: Local-accessibility values integrated in the AD 1600-route network. For each section within the AD 1600 route network local accessibility values based on network friction is given. Green areas depict well-accessible areas, yellow, orange and red poorly accessible regions.

Table 6: Agreement between LCP-calculated routes (100 m wide route zone), the ALS-extracted hollow ways, the AD 1600 route network and the TMK 1850.

Description	Outside route zone	Inside route zone	% Outside route zones	% Inside route zone
ALS-extracted hollow ways (in metres)	150314	11292	92.7%	7.3%
AD 1600 route network (in metres)	147223	14383	91.1%	8.9%
TMK 1850 routes (in metres)	108600	53006	67.2%	32.8%

this moraine, which is best explained by more complex cultural variables (e.g. socio-economic) behind the development of this route. Comparison results are best with the TMK 1850, showing that 40.0% of the routes on this map correspond with the calculated NFM-route zones. It should, however, be noted that the TMK 1850 depicts a much higher number of routes than the other two comparison datasets.

6.2. Validating the LCP model

The results of our LCP model, routes converted to 100 m-wide zones, were compared to the same datasets as those that were used in the validation of the NFM (**Table 6**). Given the agreement between the LCP routes and the ALS-extracted hollow ways, only 7.3% of the hollow ways correspond to the LCP routes. This relatively minor overlap might be explained by the partial disappearance of these routes over time. This is supported by the fact that 53.0% of the extracted hollow ways correspond with routes shown on the TMK 1850, which suggests that local hollow ways are better preserved than long-distance ones. The agreement between the LCP routes and the AD 1600 network is slightly higher than with the ALS-extracted hollow ways: 8.9% (**Table 6**). This still relatively minor overlap is best explained by the fact that Horsten (2005) in his overview did not reconstruct the complete route network and only focussed on the most important connections. Additionally, the very small applied route zone of 100 m and the incompleteness of the model further hamper results. Since we selected the LCP routes based on their confirmed existence in historical sources, agreement with the TMK 1850 is (not surprisingly) the highest: 32.8% (**Table 6**). It should, however, be noted that the TMK 1850 shows more roads and paths than the other comparison datasets. Therefore, more alternative routes are likely to fall into the 100 m route zone and variations between the individuals LCP routes are visible (for more background data see, Appendix B).

7. Discussion

7.1. Network-friction method

The high percentage of overlap between high NFM accessibility and the location of ALS-extracted hollow ways and AD 1600 routes, 99.0% and 81.8% respectively (**Table 4**), point towards a strong link between route networks and (combined) landscape setting. Although the NFM does not predict the location of individual hollow ways it does calculate regions where remnants of these landscape features can be expected. This predictive potential of the NFM could be further increased by incorporating detailed information on past-drift sands into the model. It should however be noted that these strong agreements potentially are positively influenced by the general high level of accessibility of the Veluwe region (66.9% well-accessible areas). Therefore to further test the applicability of the network-friction approach a similar NFM should be applied on more dynamic lowland areas, such as river areas.

In contrast, route zones calculated through the NFM show relatively little agreement with the ALS-extracted hollow ways and AD 1600 routes. There are various explanations for the minor overlap between NFM-route zones and the ALS-extracted hollow ways (2.3%; **Table 5**). First, scale differences between the two methods most likely play a role. Where the NFM-route zones were designed to model supraregional connections, the ALS-extracted hollow ways (based on orientation) appear to reflect a more local network of paths and tracks (Section 6.1). In order to determine whether the NFM can be used to also model these local paths and tracks, grid-cell resolution and especially input-data resolution should be greatly increased in the future. Second, the NFM specifically was designed to reconstruct route zones around AD 1500. The ALS-extracted hollow ways lack chronological differentiation and can only be dated relatively. Therefore part of the ALS-extracted hollow ways could actually reflect preceding or postdating time frames. Third, both the NFM and the ALS-extracted hollow ways only reflect remnants of the old route networks. ALS data is only useful for locations where features of these routes and paths are still preserved in the landscape, and preservation strongly depends on geomorphological stability (non-dynamic sandy areas) and cultural conditions (e.g. non-densely populated or cultivated areas). Fourth, the current NFM-route zones currently lack a differentiation between different types of routes (e.g. route hierarchy); adding such detailed (historical) data to the model would probably benefit modelling results further.

Agreement between the NFM-route zones and the AD 1600 route network is much higher, but still only 29.2% (**Table 5**). This is best explained by the spatial resolution of the NFM and the method behind route-zone calculations. First, in our agreement calculations we used 100 m wide route zones, despite the fact that many of these zones could actually be several hundreds of metres wide (Section 2). In this respect, the overlap percentage reflects a minimum amount of corresponding routes and actual overlap percentages might be higher. Second, NFM-route zones were designed to reconstruct large-scale connection transport zones (Section 2). The method was not designed to model routes on a detailed regional scale, which would require a more dense network with multiple connections between nodes. In order to determine the full potential of the network-friction method, NFM-route zones could incorporate more detailed network analyses and LCP calculations in combination with more detailed geoscientific data. **Figure 8**, however, shows that despite the low overlap percentage between the NFM-route zones and the AD 1600 network, many parts do line up, and increasing route-zone widths would probably lead to much higher agreements. The most notable exception is the route running over the high push moraine in the centre of the study area. Here, the NFM fails to calculate a route zone since no nearby settlement data are available. The probably socio-economic origin of this route reconstructed by Horsten (2005) fundamentally differs from the (Roman and early-medieval) variables defined by Van Lanen et al. (2015b). In order to also model these kinds of routes, other input variables, specifically designed for this historical period, should be developed for the NFM.

One of the aims of the current study was to determine the applicability of the network-friction method on a more detailed, regional scale and a different historical period. The method originally was designed specifically for the Roman period and Early Middle Ages, but this study shows that the approach does have potential in reconstructing more recent route networks. Since the NFM is an accumulative model the number of input datasets can be potentially endless, making the model flexible and especially accurate in reconstructing past accessibility based on landscape prerequisites. Although the models' resolution was increased by decreasing grid-cell size from 500 × 500 m to 100 × 100 m, agreement percentages (**Table 5**) show that NFM route-zone calculations probably benefit from a) more detailed geoscientific input data (<1:50,000), including high-resolution vegetation reconstructions, and b) modelling techniques from network and least-cost path analyses.

7.2. Least-cost path method

The LCP-calculated routes agree best with the TMK 1850 dataset. This is not surprising, because a) this map shows a much higher number of (alternative) roads and paths and b) the LCP-calculated routes reflect preselected trajectories of routes known to be in use during the 19th century (Section 4.3; Appendix B). Based on the LCP model it has become clear that terrain appears to have been the forcing factor in route-network orientation, followed by groundwater levels and slope. However, the model also shows that forcing factors can differ per individual route section (Appendix B). Consequently there is not one factor dominating route orientation in the Veluwe and each LCP route actually should be investigated individually. For example, avoiding lower, wet areas was especially important for route sections between Arnhem – Harderwijk which ran on the west brink of the push moraine and Hattem – Voorthuizen near the coast. If merely slope would have been the forcing factor for these routes, these lower areas would have been best suited for the network and agreement with the TMK 1850 even lower. In some cases, like the route Dieren – Barneveld the forcing factor is difficult to assess and cultural factors especially appear to have been in play (Appendix B). The diversity in forcing factors do point towards the need of applying flexible modelling which incorporates changing local accessibility settings based on a multitude of datasets.

The LCP model applied in this paper calculates routes based on weight values derived from terrain, slope and groundwater-level factors. Terrain coefficients were quantified based on scientific data (Soule and Goldman, 1972). However, many of other weight values were determined based on expert judgement. For example, in determining the terrain factor, threshold values were determined based on a combination of the soil map, DTM and the TMK 1850 (Appendix B). Therefore these threshold values depict the present-day situation and may differ slightly from the historical situation around AD 1500. The same bias applies to the factor slope, which was calculated based on current elevation data in the study area. It is currently impossible to determine the exact differences between the historical and present-day situation. Therefore the LCP model would benefit from more detailed geoscientific input data reflecting the period around AD 1500.

7.3. Methodological integration

This study shows that route-network modelling using GIS improves our understanding of past route networks in the Veluwe region. Agreement results are best for the network-friction approach. Through the accumulative nature, the NFM integrates multiple geoscientific datasets and provides dynamic local accessibility values for entire route trajectories, which allows to compensate for changing forcing factors. Route zones calculated by the NFM appear to mainly reflect thoroughfares in the study area. These NFM-route zones show the best agreement in the lower areas where movement corridors are most pronounced. Through the integration of multiple datasets the NFM also allows to locate omissions in other datasets. For example by comparing the NFM with the AD 1600 network we were able to locate areas with a high-accessibility level and an abundance of settlements and therefore increased likelihood of route occurrence not reconstructed by Horsten (2005) (**Figure 10**). Agreement results for the LCP model were lower compared to the NFM but did show the necessity of incorporating multiple landscape variables when calculating individual LCP

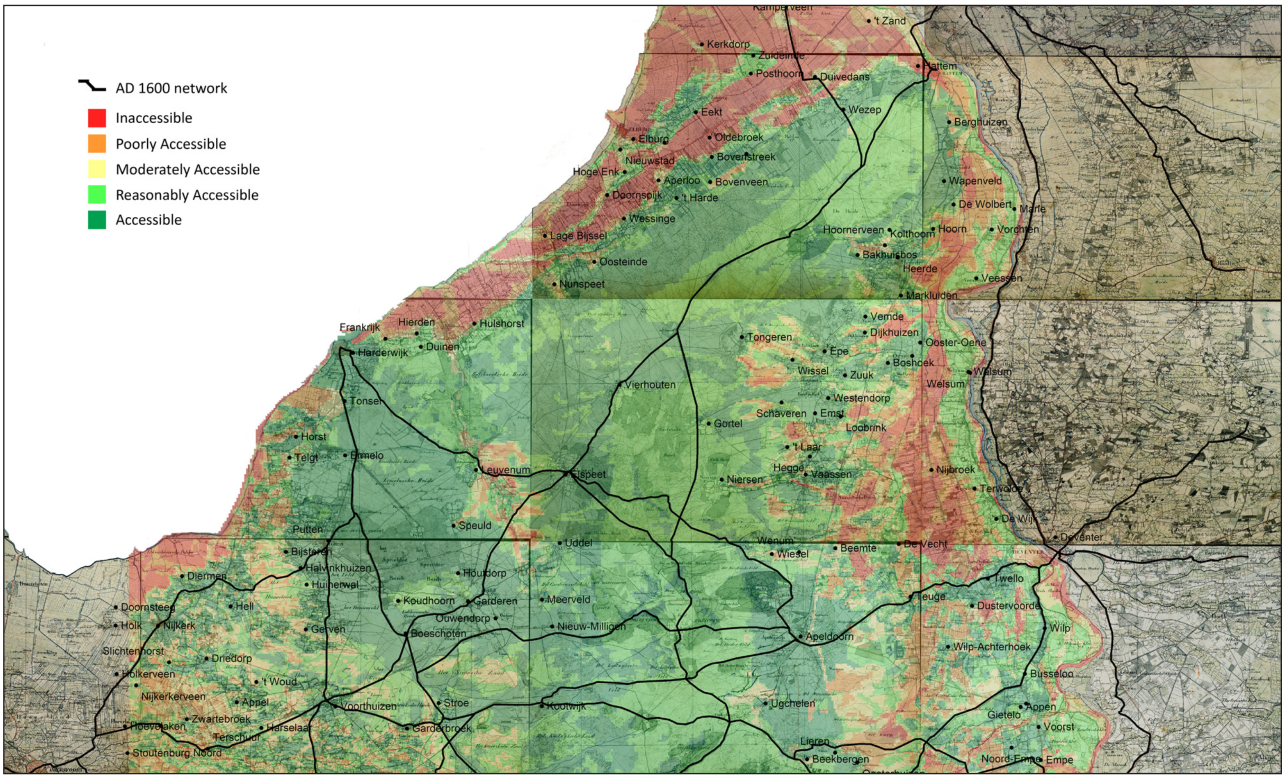

Figure 10: Network-friction map overlaid on the TMK 1850 and the AD 1600 road map by Horsten (2005) for the northwestern part of the study area. In this section, for example, it is clearly visible that not all AD 1600 routes connect settlements, reflecting the fragmentary state of AD 1600 route network. Based on the NFM, movement corridors are reconstructed which can point towards probable missing route-zone connections. For example connecting thoroughfares can be expected running from west to east in the northern part of the study area.

routes, i.e. different sections within one route can have different forcing factors. Both modelling approaches show potential for route-network modelling on the Veluwe and could be further integrated in the future. Where network friction provides dynamic local accessibility values, the LCP modelling allows for the calculation of specific movement conditions which could benefit the NFM-route zone modelling on this more detailed regional scale in order to also include more local paths and tracks in less pronounced movement corridors.

8. Conclusion

In this study we have applied and compared two different route-network modelling techniques in order to optimally reconstruct route networks around AD 1500 in the Veluwe region. We were able to determine that the central part of the study area appears to have been relatively well accessible. In the western, lower parts the presence of peat and clay must have limited route options, resulting in few and narrow movement corridors. To the south and east accessibility was bound by the rivers Rhine and IJssel and to the north by the sea (Zuiderzee). Although the study area in general is well accessible, routes appear to have mainly run along the borders and not through its central part. This is underlined by the lack of settlements in this area. Consequently, east-west routes predominantly appear to have run alongside, and not across, the largest push moraine.

Both the NFM and LCP model we have applied in this paper successfully modelled parts of the route networks around AD 1500. Agreement results with comparison datasets are highest for the NFM, which shows great potential in reconstructing past local accessibility and thoroughfares based on integrating multiple datasets. The NFM however has difficulties reconstructing more local, micro-regional connections. This study shows that it is possible to increase the grid-cell resolution of a NFM to 100 × 100 m, but that much is to be gained by increasing the resolution of geoscientific and cultural input data. The more traditional LCP model was especially successful in determining different forcing factors behind route development, but agreement results with comparison data on route network are generally low. However, the model does show the need for incorporating multiple factors during LCP calculations. Both models prove quite useful for route-network modelling on a regional scale, reconstructing parts of past networks. Because regional and micro-regional route networks are characterized by multi-scale variability, i.e. supraregional, regional and micro-regional connections are all entwined, studying these spatial structures requires a more integrated multi-proxy approach.

Notes

[1] For more information on OpenStreet data and mapping, see www.openstreetmap.org (accessed 17-11-2015).

[2] Histland contains data on the reclamation and dynamics of the Dutch landscape. For more information, see http://landschapinnederland.nl/bronnen-en-kaarten/histland (accessed 17-11-2015).

[3] This dataset was developed in 2015 by the Cultural Heritage Agency of the Netherland. See http://archeologieinnederland.nl/bronnen-en-kaarten/archeologische-landschappenkaart (accessed on 17-11-2015).

Additional Files

The additional files for this article can be found as follows:

- **Appendix A.** Network friction. DOI: https://doi.org/10.16993/rl.35.s1
- **Appendix B.** Least-cost path (LCP) calculations. DOI: https://doi.org/10.16993/rl.35.s2

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Competing Interests

The authors have no competing interests to declare.

Authors Information

Willem F. Vletter and Rowin J. van Lanen are contributed equally to this work.

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