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13 Using Citizen Science to map hollow roads in LiDAR data from the Netherlands. Results from the Heritage Quest project

13.1 Introduction

Hollow roads are linear, sunken tracks resulting from the intensive, continuous passage of carts and other traffic along specific routes through the landscape.[1] Wherever the soil was soft and could be turned aside, parallel lanes would develop over time as travellers preferred to keep to the beaten track to make for greater speed and reduce the risk of getting lost. When a track became impassable due to seasonal conditions or general wear over time, travellers were forced to shift to an adjacent lane, resulting in the pattern of parallel cart-ruts, also called route zones.[2] Such hollow roads can be found all over Europe and may date back as far as the Bronze Age (2000–800 BC),[3] although the earliest confirmed routes in the Netherlands only date back to the late Middle Ages (1250–1500 AD).[4] Generally, these tracks are hard to discern in the present-day terrain due to their superficial nature. Nevertheless, the systematic mapping of hollow roads can provide valuable information on historical route networks – the result of the deliberate movement of people within the landscape – on both an inter-site and inter-regional level.[5] These routes reflect and influence (large-scale) cultural and landscape processes,[6] and play a crucial role in the exchange of resources, knowledge, and ideas.[7] Especially, the mapping of roads on a local and regional scale can enhance and expand the knowledge gained from historical written sources and cartographic data.[8]

Fortunately, hollow roads appear as distinct longitudinal objects in airborne Light Detection And Ranging (LiDAR) data,[9] even when these are located under forest

1 *Kirchener* et al., Spatial analysis hollow ways (2020).
2 *Vletter/van Lanen*, Finding vanished routes (2018).
3 *Brongers*, Air photography (1976).
4 *Vletter/van Lanen*, Finding vanished routes (2018).
5 *Mlekuž*, Roads to nowhere? (2013); *Nuninger* et al., Developing FAIR Ontological Pathways (2020).
6 *Vletter/van Lanen*, Finding vanished routes (2018).
7 *Løvschal*, Ways of wandering (2013).
8 *Slamova* et al., Dependence medieval settlements historical roads (2014).
9 *Historic England*, Using Airborne Lidar (2018).

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or vegetation cover. This has opened up fast tracks of land – hitherto difficult to investigate – for analysis, which is generally done manually by one or a small group of experts. However, the sheer amount of available high-quality data necessitates the use of alternative strategies to effectively and efficiently map the overwhelming amount of hollow roads, i.e. computational approaches or citizen science. The former generally use more traditional spatial and predictive modelling,[10] or specialised (hand-crafted) feature extraction and analysis techniques to map roads.[11] Recently, computational approaches based on a combination of Deep Learning and geospatial processing have also shown their effectiveness.[12]

Citizen science, on the other hand, uses the active involvement of large groups of volunteer (i.e. non-professional) scientists, generally called citizen researchers,[13] in the scientific process. The participation of many individuals allows for generating and/or analysing large amounts of data and the same research action can be repeated. This replication is essential to increase the quality of the results of citizen science.[14] Although community engagement and participation in archaeology has long been a recurrent practice,[15] involving citizen researchers in the collection and/or interpretation of data is yet uncommon (but see[16]). In the following, a novel project called Heritage Quest – in which thousands of citizen researchers analysed LiDAR images for potential hollow roads – will be presented and discussed among others with reference to the potentials of this approach in studying early medieval mobility.

13.2 The Heritage Quest project

The Heritage Quest project, run by Leiden University and regional heritage organisations *Erfgoed Gelderland* and *Landschap Erfgoed Utrecht*, is the first large-scale citizen science project involving the archaeological interpretation of remotely sensed data in the Netherlands.[17] The aims of the project are twofold: on the one hand, the project intends to discover and map as yet unknown archaeology. On the other hand, it tries to

10 *Verhagen/Nuninger/Groenhuijzen*, Modelling Pathways Movement Networks (2019).

11 *Sevara* et al., Pixel versus Object (2016); *Vletter*, (Semi) Automatic extraction roads (2014); *Vletter/van Lanen*, Finding vanished routes (2018); *Kirchener* et al., Spatial analysis hollow ways (2020).

12 *Verschoof-van der Vaart/Landauer*, CarcassonNet (2021); *Verschoof-van der Vaart/Landauer*, Transferability of CarcassonNet (2022).

13 *Eitzel* et al., Citizen Science Terminology Matters (2017).

14 *Bourgeois/Kaptijn/Verschoof-van der Vaart/Lambers*, Assessing Quality Citizen Science (2024); *Kosmala/Wiggings/Swanson/Simmons*, Assessing Data Quality Citizen Science (2016).

15 *Dries*, Community Archaeology Netherlands (2014).

16 *Duckers*, Bridging geospatial divide archaeology (2013); *Lin/Huynh/Lanckriet/Barrington*, Crowdsourcing the unknown (2014).

17 *Lambers/Verschoof-van der Vaart/Bourgeois*, Integrating Dutch Archaeological Prospection (2019).

raise awareness of the rich and diverse archaeological heritage of the Netherlands, leading to better protection of this, often fragile, legacy. Two iterations of the Heritage Quest project were conducted in 2019 and 2020, respectively. The first iteration, in 2019, focused on the *Veluwe* region in the central part of the Netherlands.[18] In 2019, more than 2000 citizen researchers mapped thousands of potential prehistoric barrows (small, round or oval-shaped earthen mounds that demarcate the burial place of a select group of people), Celtic fields (parcelling systems composed of adjoining, roughly rectangular, embanked plots, which form a characteristic checker-board pattern), and medieval charcoal kilns (circular platforms or mounds surrounded by a shallow ditch or circle of pits, used for the production of charcoal) in an area of approx. 2000 square kilometres (universiteitleiden.nl/en/erfgoed-gezocht/veluwe). The second iteration of the Heritage Quest project, conducted in 2020, focused on another forested region in the central part of the Netherlands, namely the *Utrechtse Heuvelrug* (Figure 13.1). Here the citizen researchers mapped – alongside barrows and Celtic fields – hollow roads. The following will focus on this iteration of the Heritage Quest project.

13.3 Research Area and Datasets

13.3.1 Research area

The *Utrechtse Heuvelrug* (approx. 350 square kilometres) is characterised by ice-pushed ridges or push moraines formed during the Saale glacial period (roughly 350,000 to 130,000 years ago), which were partly covered by cover-sand deposits during the Weichselian glacial period (approx. 115,000 to 10,000 years ago). The process resulted in a rolling landscape with significant elevation differences.[19] Initially, the higher parts of the area were covered by forests and heath, surrounded by marshes and river valleys.[20] However, from prehistoric times onwards, the area was gradually deforested, culminating in significant deforestation in the second half of the Middle Ages (approx. 1000 to 1500 AD), which led to the formation of large drift-sand areas.[21] Large parts of the *Utrechtse Heuvelrug* were reforested in the late nineteenth and early twentieth centuries, resulting in today's extensive forests interspersed with heathlands.

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18 *Lambers/Verschoof-van der Vaart/Bourgeois*, Integrating Dutch Archaeological Prospection (2019).
19 *Berendsen*, Vorming van het land (2000).
20 *Doorenbosch*, Ancestral Heaths. Reconstructing Barrow Landscape (2013).
21 *Koster*, European Aeolian Sand Belt (2009).

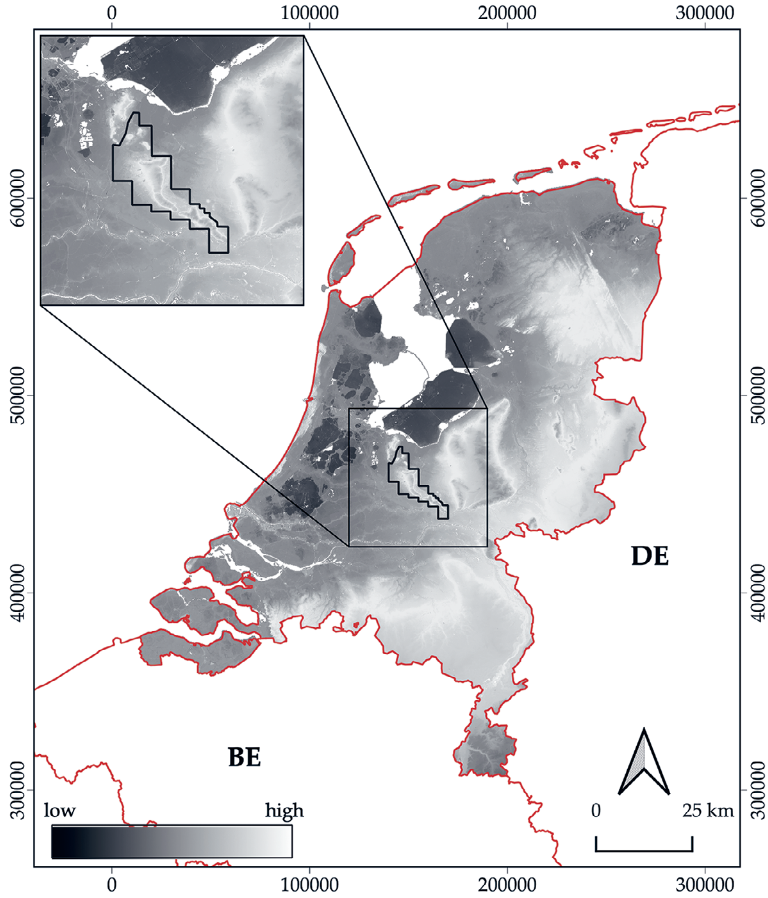

Figure 13.1: The research area (black outline) on an elevation model of the Netherlands (source of the elevation model: Nationaal Georegister 2023; coordinates in Amersfoort/RD New, EPSG: 28992; amended from Lambers/Verschoof-van der Vaart/Bourgeois [2019]).

13.3.2 LiDAR data

Airborne LiDAR is a remote sensing technique comparable to radar that can be used to create high-resolution elevation maps of the earth surface.[22] One of the big advantages of this technique, compared to other remote sensing methods, is the possibility of measuring through forest and other vegetation cover. LiDAR data for the entire Netherlands are commissioned on a regular basis by the Dutch Directorate-General for Public Works and Water Management and are freely available from the online

22 *Historic England*, Using Airborne Lidar (2018).

repository PDOK.[23] The second version of this nationwide dataset (called *Actueel Hoogtebestand Nederland* 2 or AHN2) was used in this research and has an average ground point density of 6 to 10 per square meter, a spatial resolution of 50 centimetres and a vertical and planimetric accuracy of 5 centimetres.[24]

13.4 Methodology

13.4.1 Online system

To analyse the LiDAR data from the research area, an online system was hosted on *The Zooniverse*, a web-based platform that allows people from all over the world to participate in citizen science projects without having any specialised background, expertise, or training.[25] In the Heritage Quest project, participants were asked to mark every potential barrow, Celtic field, and hollow road they could see within a small LiDAR image.[26]

These images were obtained by dividing the LiDAR data of the entire research area into images of 300 by 300 metres (600 by 600 pixels) with a small overlap to all sides. The participants were presented with two different LiDAR visualisations, i.e. shaded relief or hill shade and Simple Local Relief Model[27] to assist them in their classification (Figure 13.2). The first visualisation is more commonly used and was more intuitively interpreted by volunteers. Meanwhile, the second visualisation allowed for better detection of faint traces since it enhances the local detail, while suppressing the large-scale terrain relief.[28]

Throughout the project, a dedicated staff member assisted by a team of volunteers monitored user engagement, providing feedback and online support through an accompanying forum. When starting, participants were provided with a short tutorial on how to operate the website and how to identify the archaeological objects. A *Field Guide* – featuring more in-depth background information on the project, the archaeological objects and region under investigation of interest, as well as archaeological prospection and remote sensing in general – could be consulted at any time. The interface on *Zooniverse* was bilingual Dutch/English, ensuring both international citizen researchers – as well as Dutch-speaking volunteers – could participate.[29]

Since the citizen researchers were neither trained in archaeology nor in remote sensing, showing every image to only one individual would result in noisy, possibly

23 *Nationaal Georegister*, Publieke Dienstverlening Op Kaart (PDOK) (2013).
24 *Zon*, Kwaliteitsdocument AHN-2 (2013).
25 *Simpson/Page/De Roure*, Zooniverse (2014).
26 *Lambers/Verschoof-van der Vaart/Bourgeois*, Integrating Dutch Archaeological Prospection (2019).
27 *Kokalj/Hesse*, Airborne laser scanning data visualization (2017).
28 Ibid.
29 *Bourgeois/Kaptijn/Verschoof-van der Vaart/Lambers*, Assessing Quality Citizen Science (2024).

Figure 13.2: The Heritage Quest mapping interface on *Zooniverse*, showing the two LiDAR images with different visualisations and the current task (after Lambers/Verschoof-van der Vaart/Bourgeois [2019]).

unusable data.[30] Therefore, in the Heritage Quest project, every individual LiDAR image was shown not to one but to sixty different volunteers before it was retired (i.e. taken out of the set of available images). The concept behind this iterative process is that when multiple participants investigate every image, a consensus is reached between users at a certain point. Archaeological objects that perfectly fit the examples shown beforehand in the tutorial will be identified by all (or the majority of) the participants, while less likely candidates are only selected by a few people. Moreover, accidental errors can be easily filtered out through this method, as two people will never accidentally mark the (exact) same location.[31] Therefore, locations marked by only one citizen researcher are very often mistakes or misclassifications.

13.4.2 Post-processing

To aggregate and analyse the results of the online project, the data from *Zooniverse* (i.e. all individual detections of hollow roads) were converted into geospatial entities (i.e. polygons) with real-world coordinates in a Geographic Information System (QGIS 3.16 Hanover[32]). Secondly, a division was made between the detections of hollow roads, based on their location within the landscape. Research has shown that certain landscape characteristics, such as current land-use, have an influence on the preservation

30 *Kosmala/Wiggings/Swanson/Simmons*, Assessing Data Quality Citizen Science (2016); *Swanson/Kosmala/Lintott/Parker*, generalized approach citizen science data (2016).
31 *Bourgeois/Kaptijn/Verschoof-van der Vaart/Lambers*, Assessing Quality Citizen Science (2024).
32 *QGIS Development Team*, QGIS (2017)

and/or visibility of hollow roads and on the number of incorrect detections caused by 'objects of confusion', i.e. those morphologically comparable to hollow roads.[33] Consequently, hollow roads generally have the best chance of survival in areas covered with forest or vegetation, such as heathland. The likelihood of discovering hollow roads outside of those areas is generally very low (circa 1.5%).[34] Therefore, all polygons outside of areas covered with forest, heather, or grasslands, were removed. These areas were determined based on the map *present day land-use*, created by CBS Statistics Netherlands (pdok.nl/introductie/-/article/cbs-bestand-bodemgebruik). The remaining "stacks" of overlapping polygons were made partially transparent in the GIS. The latter clearly showed areas marked by multiple participants in darker shades, versus areas that were marked by a single individual or a few people in lighter shades. However, the resulting dataset is inherently messy and noisy and must be critically assessed before these can be used for further research.[35] Therefore, all polygons were manually analysed by the first author to remove False Positives (i.e. errors or misidentifications) from potential hollow roads.

13.5 Results

13.5.1 General results

The Heritage Quest project on the *Utrechtse Heuvelrug* was launched in April 2020 and succeeded in mapping the entire area (circa 350 square kilometres) in approximately one month. Over 4572 citizen researchers participated, resulting in a total of 300,971 individual images being classified. In the course of the project, 35,558 individual detections of hollow roads were made (Table 13.1). After converting the results into geospatial data and ensuring the removal of polygons outside of forest, heathland, and grassland, 33,341 polygons remained. The manual analysis, which took roughly seven hours, could eliminate another 10,000 False Positives, resulting in 23,664 polygons. In turn, these could be combined into 584 demarcated areas with a total coverage of approx. 31,756,000 square meters.

To evaluate the performance of the Heritage Quest project, the areas (in square metres) of True Positives (TP) and False Positives (FP) were determined, following the approach taken in Verschoof-van der Vaart and Landauer (2021). Subsequently, Precision (Equation 1) – a metric that measures how many of the selected areas are relevant – was calculated. Precision is restricted between 0 and 1, with a higher value

33 *Verschoof-van der Vaart/Lambers/Kowalczyk/Bourgeois*, Deep Learning Location-Based Ranking (2020).

34 *Verschoof-van der Vaart/Landauer*, CarcassonNet (2021).

35 *Kosmala/Wiggings/Swanson/Simmons*, Assessing Data Quality Citizen Science (2016).

indicating better performance, i.e. fewer False Positives. The citizen researchers in the Heritage Quest project reach a Precision of 0.44 (based on square meters). When calculated using the number of polygons, the Precision is much higher, reaching 0.71. In the former scenario, the actual area marked by the volunteers is the main influence on performance, while in the latter what exactly is marked is ignored. Instead, the number of markings made by the citizen researchers is of primary importance.

The sizable difference between these two values could indicate that on average the citizen researchers tend to mark the right areas (i.e. areas with hollow roads), while wrong areas are only marked by one or a few individuals. However, as shown by the lower Precision value – based on area (square meters) – the delineations of these areas are not always very accurate. This inaccuracy is owing in part to confusion among the volunteers about the level of detail with which the hollow roads needed to be marked on the online platform. For instance, when many hollow roads were present in a single image, citizen researchers often outlined the entire image instead of only the hollow roads. This shows that clear instructions on the level of detail are essential to the success of citizen science. Additionally, the task must not be too time consuming/laborious.

Equation 1.
Precision = TP/(TP + FP)

Table 13.1: Results of the post-processing of the Heritage Quest detections.

Process	Detections/Polygons	Square metre
Heritage Quest results	35,558	86,949,381
Only roads in forest, heathland, or grassland	33,341	72,352,231
Manual analysis	23,664	31,765,000

A cursory analysis of the results shows that both larger bundles of multiple hollow roads, as well as smaller bundles and individual tracks are recognised by the citizen researchers (Figure 13.3, A and B). False Positives include a wide range of anthropogenic and natural landscape elements that generally have a comparable shape to hollow roads. These include (planting) ditches (Figure 13.3, C), plough marks, (forest) paths (Figure 13.3, E), and modern tracks made by agricultural vehicles (Figure 13.3, D). Interestingly, False Positives seem to be concentrated near the edges of the research area, i.e. farther away from the high-lying push moraine in the centre of the research area. This might be related to the increased presence of agricultural activity in these low-lying zones.

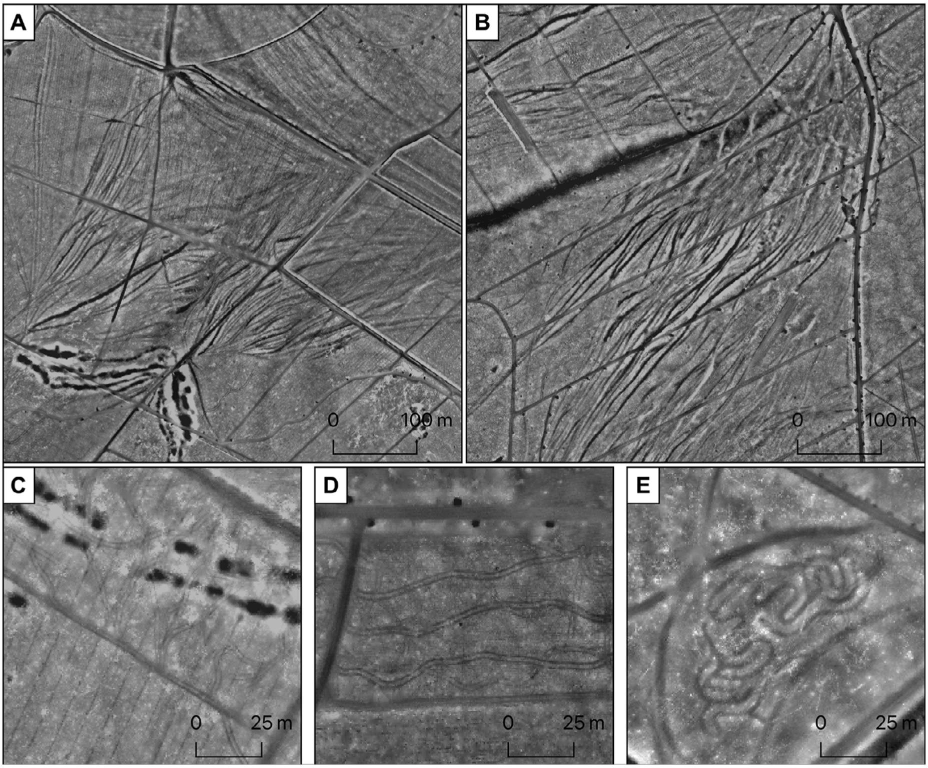

Figure 13.3: Excerpts of LiDAR data (source: Nationaal Georegister 2023), visualised with Simple Local Relief Model, from the research area, showing: Examples of bundles of hollow roads (A and B); planting ditches (C); vehicle tracks (D); modern (forest) paths including a maze (E).

13.5.2 Comparing citizen science to automated detection

The performance of our citizen science approach can be compared to a recent computational approach, named CarcassonNet, that has been used to map hollow roads in LiDAR data from the Netherlands.[36] Interestingly, both methods reach a comparable level of Precision (based on square meters), with CarcassonNet having a Precision of 0.41 versus a Precision of 0.44 for the Heritage Quest project. This is surprising, given that other research outcomes – when comparing the performance of automated detection to citizen science for the mapping of archaeology in LiDAR data – revealed a significant discrepancy between the Precision of both methods, with citizen research-

36 *Verschoof-van der Vaart/Landauer*, CarcassonNet (2021); *Verschoof-van der Vaart/Landauer*, Transferability of CarcassonNet (2022).

ers reaching much higher Precision.[37] The comparable Precision between CarcassonNet and Heritage Quest shows that this particular task, i.e. mapping hollow roads in LiDAR data, is not as easy as mapping other archaeology, e.g. barrows. Even though the citizen researchers have the additional advantages of being able to consult two different LiDAR visualisations (while the automated detection is done on one visualisation) and can observe the direct vicinity of the potential hollow roads.[38]

13.5.3 Reconstructing route networks

Based on the results of the Heritage Quest project, the route networks in the research area can be analysed (Figure 4). This shows many, north–south orientated routes in the southern part of the research area. The central part of the research area shows a clear triangular pattern in the roads, while in the northern part no clear pattern is visible. Part of this pattern is the result of the geo(morpho)logical situation of the local landscape. For instance, a concentration of hollow roads can be observed north of the town of Leersum (Figure 13.4). These can be related to the largest ice meltwater valley (*ijssmeltwaterdal*), called the *Darthhuizerpoort*, which dissects the push moraine[39] and effectively offers a passage through the *Utrechtse Heuvelrug*. Based on the number of hollow roads in this area, this passage has been extensively utilised.

The observed route networks can, in large part, also be related to areas of habitation in and around the direct vicinity of the research area. This distribution of settlements originates in the early medieval Carolingian period (roughly 750–900 AD), with the emergence of so-called *flankesdorpen* or *engdorpen* (esdorp or angerdorf) on the lower flanks of the push moraine (Figure 13.4).[40] These villages are characterised by houses and farmsteads laid out around a central open area, called the *brink* or the village green, while the village itself flanks one side of a communal agricultural complex (the *es*). Communal pastures (often heathland) were situated on the higher parts of the *Utrechtse Heuvelrug*. Especially in the southern half of the research area, we can observe concentrations of hollow roads in the vicinity of these villages, for instance the village of Maarn.

Many of the major routes connect different cities and settlements, such as the triangular shaped routes in the centre of the research area that connect the village of Maarn in the south, the village of Oud Leusden and the city of Amersfoort in the north, and the village of Zeist and the city of Utrecht in the west. In some cases, mapped hollow roads can even be linked to (modern) roads. For example, hollow

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37 *Verschoof-van der Vaart/Lambers/Kowalczyk/Bourgeois*, Deep Learning Location-Based Ranking (2020).
38 *Verschoof-van der Vaart*, Learning to look at LiDAR (2022).
39 *Berendsen*, Vorming van het land (2004).
40 *Berendsen*, Landschappelijk Nederland (2000).

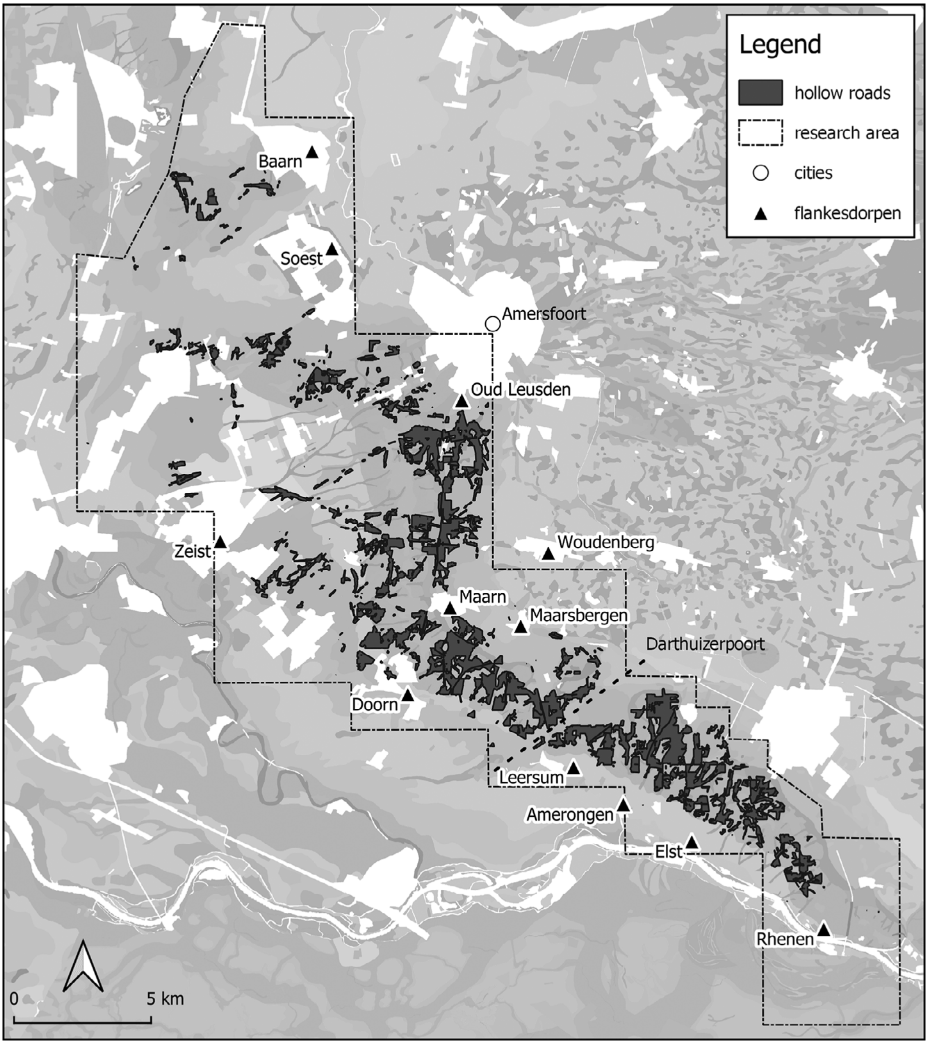

Figure 13.4: So-called *flankesdorpen* or *engdorpen* (esdorp or angerdorf) on the lower flanks of the push moraine.

roads – forming a major extension of the *Oude Woudenbergse Zandweg* – can be observed northeast of the town of Zeist, leading eastward. The *Oude Woudenbergse Zandweg* (which loosely translates as “Old Sandroad to Woudenberg”) appears on maps from the seventeenth century; if extended with the mapped hollow roads, it connects the city of Utrecht to the village of Woudenberg, as the name of the road implies.

13.6 Discussion

The results of the Heritage Quest can be used to better understand medieval routes on the *Utrechtse Heuvelrug*. However, an important question remains concerning the date of these hollow roads. While it has been suggested that these roads can date back to the Bronze Age (2000–800 BC),[41] a "younger" date seems more likely. Based on the origin of the settlements these routes appear to relate to, a medieval (or younger) age is more probable for these roads (see Section 13.5.3).

Unfortunately, it has proven difficult to obtain precise dates for hollow roads, due to their superficial nature and general lack of datable finds. Recently, progress has been made in using absolute dating methods – like Optical Stimulated Luminescence (OSL), combined with archaeological excavations and historical archival research – to provide reliable dating and contextualisation of hollow roads in sandy soils on the Veluwe in the Netherlands.[42] However, these methods are costly and not all roads are suited to this approach.[43] Although the results of the Heritage Quest project could be used to determine appropriate locations and obtain samples for dating.

An alternative approach is to establish a relative chronology of hollow roads in a given area by comparing the morphology of the roads with historical information and/or cartographical data,[44] and by checking for intersections among roads, between roads, and other (dateable) landscape elements or archaeological features. For example, Figure 13.5 shows the hollow roads in a small area near the village of Maarn, on the northern flank of the *Utrechtse Heuvelrug*. This area demonstrates the complex intersections present among hollow roads. For instance, road bundle A is dissected by road bundle B, which shows that B is younger than A. Further to the north, road bundle A overlays road bundle C, which in turn overlays road bundle D. Based on this, road bundle D is the oldest, followed by C, then A, with B being the youngest. Furthermore, road bundle B runs over the drift sand deposits in the eastern part of the image, while road bundle A is overlain by drift sand in the southern part. According to Koster (2009), the majority of drift sand accumulation originated during the early part of the Late Middle Ages (after 950/1150 AD), driven by the expansion of agriculture, the grazing and burning practices of communal heathlands (overexploitation), the formation of roads and cattle/sheep drifts, and the use of plaggen fertiliser. Sand drifting also occurred during the sixteenth century and even as late as the eighteenth and nineteenth century.[45] However, based on the results from Pierik et al. (2018), most of the drift sand in the direct vicinity of Maarn can be dated between 1000 and

41 *Brongers*, Air photography (1976).
42 *Vletter/Spek*, Absolute Dating Historical Road Tracks (2021).
43 *Vletter*, Relative Chronology of Road Network (2019).
44 Ibid.
45 *Koster*, European Aeolian Sand Belt (2009).

1500 AD.[46] Therefore, road bundle A could date anywhere from the tenth century up to the sixteenth century. This example shows that, even when historical information is available, the dating of these hollow roads is a complex and elaborate task, making the development of a relative chronology for larger areas very labour-intensive, and therefore – as with absolute dating – costly.

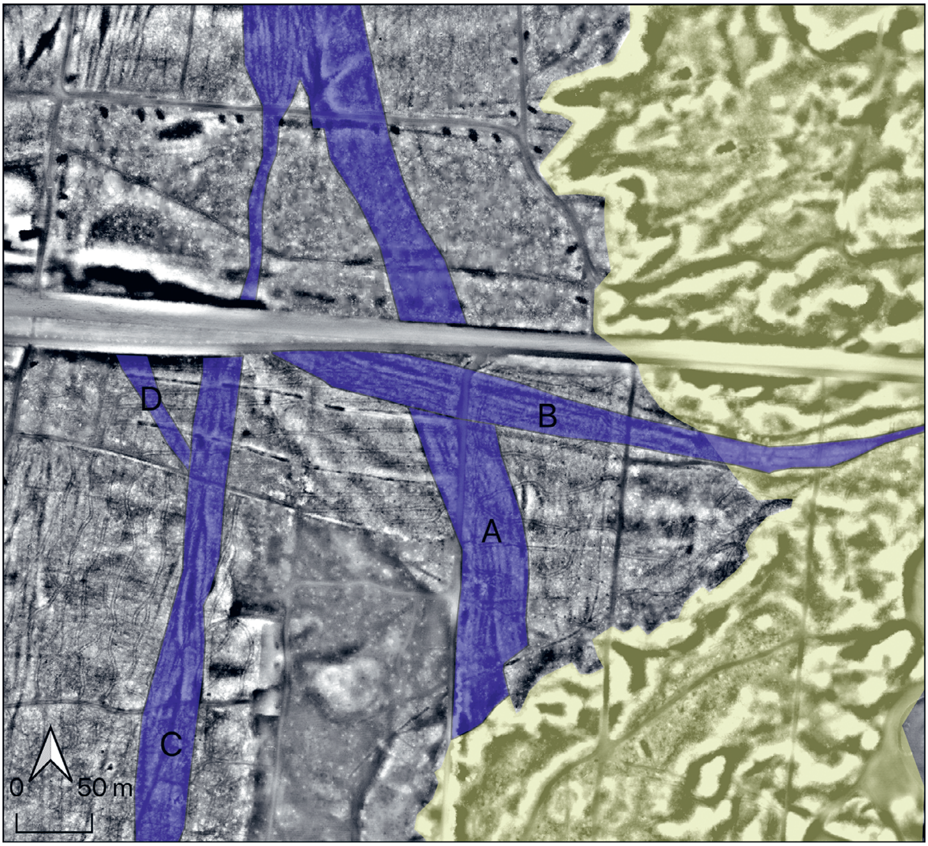

Figure 13.5: Excerpts of LiDAR data (source: Nationaal Georegister 2023), visualised with Simple Local Relief Model, showing the complex relation among hollow roads (in blue) and between hollow roads and other landscape elements, such as drift sand (in yellow).

Nevertheless, the effective mapping of hollow roads as done in the Heritage Quest project offers opportunities to investigate archaeological hypotheses on a regional or landscape scale.[47] For instance, according to Jager (1985), there is a relation between

46 *Pierik* et al., Late-Holocene Drift-Sand Dynamics (2018).
47 *Verschoof-van der Vaart/Landauer*, CarcassonNet (2021).

the choice of route of hollow roads and the location of forests. He postulates that forested areas were generally avoided due to danger of being robbed by highwaymen in these areas. Combining the results of this research with historical land-use data could offer further insight into this hypothesis. Another prevailing idea that has yet to be investigated is the relation between hollow roads and prehistoric barrows, in which the latter would serve as road markers.[48]

13.7 Conclusion

In this research, we presented a citizen science approach, named Heritage Quest, to map (medieval) hollow roads in LiDAR data from the central part of the Netherlands. The results show that the citizen researchers in the Heritage Quest project are able to effectively map hollow roads in data from the *Utrechtse Heuvelrug*. The results of this approach offer an indication of the mobility and movement of people and goods in the late medieval period. Although the dating of hollow roads remains problematic, careful examination of the succession and intersection of specific roads and routes – especially if supplemented with historical information about locations along these routes – might offer the possibility of discerning movement in even earlier periods, e.g. the early medieval period. However, convincingly assigning roads to these earlier periods is hampered by the repeated use of the same routes over long periods of time. Future research will therefore focus on the development of a relative chronology of the hollow roads in the research area. The implementation of the Heritage Quest approach in other regions is also envisioned.

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