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DEPARTMENT OF GEOGRAPHY

The Suitability of Using Least Cost Path Analysis in the Prediction of Roman Roads in the Highland and Lowland Zones of Roman Britain

by

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In submitting this dissertation, I confirm that it is my own work.

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“To recover a Roman road, […] to establish its exact alignment, even in detail, is not one of those half-futile historic tasks, whose achievement ends in itself.” - *Hilaire Beloc*

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ABSTRACT

Least Cost Path (LCP) analysis has been thought of as being environmentally deterministic, with an overemphasis of environmental factors on cultural activity (Gaffney and van Leusen, 1995; Taliaferro et al., 2010; van Leusen, 1999). Due to this, this thesis will investigate whether LCP analysis is a viable technique for predicting the location of Roman roads in two distinct zones in Roman Britain: the north and west, also known as the Highland zone, which is characterised by steep slopes and rugged mountains (Collingwood and Myres, 1936; Salway, 2001), and the south and east, known as the Lowland zone, and characterised by flat land and few hills (Collingwood and Myres, 1936; Ottaway, 2007). To do this, components within the LCP calculation that can affect the accuracy of computed LCP will be assessed, with the hypothesis proposed that LCP analysis will more accurately predict the location of known Roman roads in the Highland zone of Roman Britain due to its more mountainous terrain.

The results identified that the accuracy of the LCP computation is sensitive to the components that are incorporated into the LCP calculation, with the accuracy of the computed LCP increasing with the use of more directions in the calculation, as well as using higher resolution elevation data. In addition, the time based Márquez-Pérez et al. (2017) Modified Hiking Function produced the most accurate LCP when compared to more established cost functions, such as the Tobler's Hiking Function (1993). The comparison of the accuracy of the LCP computed for the four study areas identified that the LCPs were more accurate in the Highland zone, compared to the Lowland zone, with 65% lying within 250m from the known Roman roads in the Highland zone to 31% in the Lowland zone. Furthermore, the Higuchi viewshed was found to be an effective method at determining whether Roman roads were constructed with the need to be visible.

This thesis has determined that future LCPs analysis studies should use the highest number of directions and the highest resolution elevation data available as to ensure the most accurate LCPs are generated. In addition, multiple cost functions should be compared and assessed in order to ensure the most applicable cost function has been used. Lastly, the resultant LCPs suggest that, if social processes are poorly known, the use of LCP analysis is more appropriate for predicting Roman roads in the mountainous Highland zone, where the roads were constrained by topography. Furthermore, these findings suggest, in general, the use of LCP analysis

is more suitable to predicting ancient roads in mountainous regions, and should therefore be used with caution in areas of flat land or significant social subjectivity in the modification of the landscape

CHAPTER ONE: INTRODUCTION

In the last two decades, the reconstruction of ancient roads (e.g., Verhagen and Jeneson, 2012) and the identification of factors governing the construction of known roads (e.g., Bell and Lock, 2000; Kantner and Hobgood, 2003) using spatial modelling and Geographical Information Systems (GIS) has increased (Herzog, 2013b; Lanen et al., 2015), with Least Cost Path (LCP) analysis, which finds the optimal path connecting two geographic points (Hardin et al., 2012), becoming widespread in its usage (Orengo and Livarda, 2016). As stated by Rahn (2005; 2007), the modelling and analysis of landscapes has moved towards increasingly sophisticated techniques, with the application of LCP analysis representing a well-established methodology within archaeological GIS. Herzog (2013b, p.4) counters this, stating that the calculation of LCPs is by "no means trivial"; with van Leusen (2002, p.6.5) reflecting that the wide variety of parameters used to calculate LCPs in general is a "sign of immaturity of the field". Therefore, it is necessary to investigate the LCP calculations and the parameters used and to assess how adequately the LCP models fit archaeological reality (Herzog, 2013b).

In order to investigate LCPs as a viable technique, this study will examine the suitability of using LCP analysis to predict the location of Roman roads in two distinct zones of Roman Britain. Furthermore, there will be a significant focus on assessing how variations within the LCP calculation affect how well the LCP predicts the Roman roads.

In Roman studies, Britain is often divided into a South and East and a military dominated North and West (Millet, 1990), which this study will also adopt as its zones of analysis. According to Salway (2001), this division is in reference to the terrain of Britain, with the south and east, which are characterised by relatively low hills, gentle slopes (Collingwood and Myres, 1936), and large areas of flat land, known as the Lowland zone, whilst the north and west are known as the Highland zone, and are marked by steep slopes (Collingwood and Myres, 1936), hills, and rugged mountains. The Lowland zone became civilian areas, with the road network gradually developing to provide communications and support for the expanding civilian economy (Davies, 2002), whilst forts were moved progressively westwards and northwards (Green, 1986) as the mountainous terrain posed greater difficulty for the conquest of the Highland zone compared to the Lowland zone (Pettifer, 2000). These forts were subsequently linked by a road network, facilitating the quick and effective movement of troops and supplies (McCloy and Midgley, 2008), which aided in controlling the newly-conquered tribes (Breeze, 1987). As stated by Hopewell (2004) when discussing the west of the Highland zone, the layout of many Roman roads were dictated by the mountainous terrain, with Margary (1973) noting that aligned roads were not possible. In addition, Knapton (1996) states Roman roads deviated from a straight line in the north, where mountainous regions mitigated against constructing a straight road. Furthermore, Collingwood and Myres (1936, p.3) state that communication by land in the Highland zone is "everywhere difficult", with the landscape imposing significant challenges when invading and conquering. In contrast, land communication in the Lowland zone was easier (Collingwood and Myres, 1936; Salway, 2001), with few hills and valleys limiting travel (Ottaway, 2007).

The study of LCP analysis has been thought of as being environmentally deterministic (Gaffney and van Leusen, 1995; Llobera, 1996; Wheatley and Gillings, 2002), as cultural or social variables are difficult to model within LCP calculations (Herzog, 2013b), leading to the possible overemphasis of environmental factors as the prime mover for cultural activity (Wheatley and Gillings, 2002). However, due to the different purpose of the road network and the topographical distinction between the Highland and Lowland zone, this thesis hypothesises that the LCPs computed in the Highland zone will predict the location of Roman roads more accurately, which are more topographically constrained, whilst the Roman roads in the Lowland zone were constructed with greater topographical freedom and a greater influence of social factors determining their construction, thus being predicted less accurately.

In order to examine this, Chapter Two will review the current status of LCP analysis literature, and identify gaps where future research is needed; Chapter Three will outline the methodologies used to conduct this study; Chapter Four will report the results of the study; Chapter Five will discuss the results in relation to the field of LCP analysis and their implications on future theory, research, and practice of using LCP analysis to predict Roman roads in Roman Britain. Finally, the Conclusion in Chapter Six will seek to outline what the main findings which have arisen from this thesis mean for the future of LCP analysis and its application in the prediction of ancient roads.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

According to Herzog (2013a), “the application of least cost path techniques [..] are inadequately applied in some cases”, with Herzog (2014a) stating that the weakest component in the least cost path analysis determines its overall performance. Therefore, this chapter outlines what least cost path is, and the components that dictate the least cost path results, with the intent of determining the best practices of least cost path analysis, as well as identifying gaps within the literature, which this thesis will endeavour to address.

2.2 LCP Analysis Overview

Least Cost Path (LCP) analysis is based on the Principle of Least Effort (Zipf, 1949), which assumes that humans will use all available knowledge of a given area or task to economise their behaviour. When travelling in a landscape, humans will attempt to optimise the costs of travelling, and naturally choose the path of least resistance (Surface-Evans and White, 2012), a real-world equivalent of an LCP (Herzog, 2013b). Therefore, the likelihood of interaction between humans and the landscape is directly related to ease of access (Surface-Evans and White, 2012). By using LCP analysis, the optimal connection between locations based on distance between the points and the effort needed to cover the distance can be found (Verhagen and Jeneson, 2012), allowing archaeologists to formulate reconstructions of extinct connections between people and places (Surface-Evans and White, 2012). As noted by Surface-Evans and White (2012), the application of LCP analysis depends on the archaeological question that is being addressed. For instance, the routes taken when first introduced to a landscape can be considered to have an optimal and a random component (Saerens et al., 2009). Although at first the contribution of the random component is very high, this diminishes over time as routes are optimised (Herzog, 2013b). Thus, LCP analysis only calculates the optimal route component, and should not be used to model once-in-a-lifetime journeys, such as crusades, where the optimal routes are rarely taken (Herzog, 2013b). Instead, LCP analysis should be used to reconstruct patterns of human movement in space (Herzog, 2013a), such as ancient roads (Güimil-Fariña and Parcero-Oubiña, 2015; Siart et al., 2013) and trade routes (Batten, 2007; Stanish et al., 2010), which Güimil-Fariña and Parcero-Oubiña (2015) state are designed to follow the route that requires the least effort in terms of movement.

2.3 LCP Calculation Overview

As stated by Surface-Evans and White (2012), there are two types of data that are necessary for building LCP models: cultural and environmental. Cultural data, such as the location of settlements, form the basis of the cultural landscape, and identify the start and end points of the interaction between people and places (Surface-Evans and White, 2012). The remaining data needed to create a LCP model are environmental features of the landscape, such as slope, vegetation cover, and viewsheds (Surface-Evans and White, 2012). Once the environmental factors, which Herzog (2014b) calls cost components, are identified, an appropriate cost function should be selected (Herzog, 2013b), allowing for the calculation of the cost of each move from a raster cell to its neighbour (Herzog, 2014a). If several cost components are included in the LCP model, a method to combine the functions should be also selected (Herzog, 2013b). From this, a final cost surface is created (Bell et al., 2002), which numerically expresses the difficulty of moving between individuals cells in a raster grid (White and Barber, 2012). The total cost value of each cell is then accumulated by a spreading algorithm (Matsumoto, 2008) to create an accumulated cost surface (ACS); this stores the accumulated costs for travelling from the origin to the destination (de Smith et al., 2007). The spreading algorithm, most commonly Dijkstra's algorithm (Herzog and Posluschny, 2011; Herzog, 2013a; Howey, 2007), operates by searching neighbouring cells for one with the lowest value, and then continues the procedure until all cells in the raster are assigned an accumulated cost value (Lee and Stucky, 1998). The ACS is then used to retrace the most efficient steps from the destination to the origin, resulting in the LCP (Herzog, 2014a).

Although the steps aforementioned are necessary for LCP generation (Herzog, 2013b), there is no single or correct way to perform LCP analysis (van Leusen, 2002), with the application of LCP analysis and the variables used largely based on the characteristics of the study area (Rissetto, 2012), as well as the archaeological questions being answered (Surface-Evans and White, 2012). Nonetheless, Surface-Evans and White (2012) suggest that several considerations must be reflected upon before proceeding with the analysis, with Herzog (2014a) stating that the LCP results should then be validated.

Therefore, the following will be reviewed:

1) What variables are necessary to include in the LCP model?
2) What data are needed to create the LCP model?

3) How will costs be measured?
4) Which software tool should be used to perform the analysis?
5) Validation of the LCP results.

2.3.1 Variables included in LCP models

Environmental:

- **Topography**

In order to provide a representation of real-world topography, digital elevation models (DEMs) are typically used (Kantner, 2012). DEMs are a set of raster cells arranged in a regular grid, most commonly rectangular (Wheatley and Gillings, 2002), that each contains a value that signifies the mean elevation across the area of the cell (Conolly and Lake, 2006).

Although DEMs are available in different resolutions and accuracies (Conolly and Lake, 2006), the choice of DEM often depends on data availability (Herzog, 2014a). Nonetheless, Kantner (2012) states that DEMs with a resolution of over 30 metres are too coarse to adequately represent the real world as experienced by humans travelling over a landscape, leading to a generated cost surface that bears little resemblance to the landscape (Wheatley and Gillings, 2002). For instance, Rademaker et al. (2012, p.35) reconstructed paths in Peru using a 90 metre resolution DEM, and described a canyon with a "~10-m-wide slot", something which the DEM cannot represent accurately. Furthermore, Conolly and Lake (2006) and Branting (2012) comment that the accuracy of the generated LCP can be effected significantly by using DEMs with different resolutions and accuracies. For example, Herzog and Posluschny (2011) calculated LCPs using 25 metre and 100 metre resolution DEMs, finding that the two generated paths followed different routes, with the 25 metre DEM following the ridge, whilst the 100 metre DEM located in the valley. Similarly, Harris (2000) reported that LCPs generated during one his experiments produced different routes when varying the resolution of the DEMs used. In contrast, the LCP analysis of archaic period sites in the Ohio Valley by Surface-Evans (2007; 2009) showed little difference in generated paths when using DEMs with 10 metre and 90 metre resolution. However, as stated by Herzog and Posluschny (2011), few authors address DEM related issues when doing LCP analysis. For example, Livingood (2012) coarsened the DEM resolution from 30 metres to 180 metres to reduce computational time, but did not evaluate the effect of this coarsening, such as the smoothing of the DEM (Herzog and Posluschny, 2011) and the possible decrease in the proportion of steep-slope cells (de Smith et al., 2007). Similarly, Rissetto (2012, p.17) reflects that it is possible that higher-resolution data might have changed the computed LCP; however, he assumes the differences are “minor”.

Furthermore, there are criticisms of using DEMs based on modern topography, as human activity and erosion can change the terrain over time (Déderix, 2015; Kvamme, 2006; Wheatley and Gillings, 2000). However, as stated by Kvamme (2006), terrain is usually considered relatively stable. Furthermore, DEMs based on modern topography are readily available (Kvamme, 2006). In addition, it is difficult and time consuming (Herzog and Posluschny, 2011), often impossible to reconstruct the past landscape in detail (Herzog, 2014b), due to incomplete or inconsistent archaeological datasets (Lambers and Sauerbier, 2006).

- **Hydrology**

According to Wheatley and Gillings (2002), movement across a landscape can be affected negatively by barriers, such as rivers, or positively due to the availability of different transport routes. For instance, Nolan and Cook (2012) commented that the Great Miami River, which ran through their study area, may have been important for river travel; however, they did not integrate this within their LCP analysis. Conversely, Surface-Evans (2012) in her LCP analysis of hunter-gatherer land use stated that the Ohio River was a significant barrier to travel between the north and south, and opted for creating two models of movement based on the ability or inability to travel on the Ohio River. Similarly, Howey (2007) integrated waterways in her study of ritual activity and social interaction in Michigan, stating that effective models of movement involves the evaluation of multiple criteria, tailored to the specificities of a given study area. In corroboration, Surface-Evans and White (2012) comments that the more variables included in the model, the better it potentially captures the representation of the past.

Cultural:

Cultural features of the landscape, such as trails, may make movement easier, whilst territorial boundaries, and ritual places can place constraints on travel (Surface-Evans and White, 2012; Rissetto, 2012). However, these are difficult to model as they often cannot be derived from geographic parameters (Herzog, 2013b; Kvamme, 2006), as well as different meaning and values being assigned to locations by different people (Lock, 2003). Furthermore, van Leusen (2002) and Bell et al. (2002) note that territorial boundaries, social divisions and cultural taboos leave little archaeological record and thus difficult to reconstruct, with van Leusen (2002, p.6.8) stating further that “it is unlikely that ‘social’ costs can be established with any degree of objectivity”. Therefore, assumptions about the social processes are often subjective (Verhagen and Whitley, 2012). Nonetheless, Herzog (2013b) states that cultural factors related to visibility are often considered in LCP calculations. For instance, route layout depends on the purpose of the path, with military roads often avoiding high observability, whereas civil roads were built with high visibility in mind (Lee and Stucky, 1998).

2.3.2 Data needed to create the LCP model

- **Cultural landscape**

According to Surface-Evans and White (2012, p.5), the cultural landscape is formed from settlement and land use data acquired through archaeological investigation, and allows for the identification of start and end point locations that delineate the “pathways of interaction” in a landscape. Although these data can be situated from archaeological objects, such as in the case of Phillips and Leckman (2012), who used the distribution of ceramics and ground stone as a proxy for residential sites, they often represent specific sites, or a more general region in the landscape (Surface-Evans and White, 2012). For example, Hudson (2012) selected point locations in areas of gentle terrain, such as plains. Similarly, Verhagen and Jeneson (2012) used the location of two villages in the Netherlands to predict the path of a Roman road. In addition, Güimil-Fariña and Parcero-Oubiña (2015) used regional capitals and secondary settlements to predict a Roman road situated in the Iberian Peninsula. However, many studies (eg., Newhard et al., 2008; Rademaker et al., 2012), fail to detail the positional accuracy of the site locations, which Surface-Evans (2012, p.136) states is “of paramount importance”.

- **Environmental features**
  - **Slope**

Slope has had a long history of use in LCP analysis (Kantner, 2012), as it is a critical element for all pedestrian travel (Howey, 2007). As defined by Li et al. (2004, p.20), “slope is the first derivative of altitude on a terrain surface”, and measures the rate of change in elevation over distance (Zhu, 2014). According to Herzog (2013b), “nearly all archaeological LCP studies are based on slope”, however Lock and Pouncett (2010) comment that there has been little consideration of the methodological implications of slope calculation that underpin the LCP analysis, with Warren (2004) noting that different algorithms used to calculate slope can result in significantly different slope values. Lock and Pouncett (2010) used different computational methods for slope calculation and found that different slope values were produced, leading to variations in the computed LCP. From this, Lock and Pouncett (2010) recommended slope computation based on altitude data of an n x n local neighbourhood, finding that variations in the values of slope introduced as result of error can be reduced by increasing the size of the neighbourhood window used to calculate slope, however this requires complex map algebra and is computationally intensive. Furthermore, the algorithms chosen for slope estimation are rarely discussed (Herzog and Posluschny, 2011). For instance, neither Güimil-Fariña and Parcero- Oubiña (2015) nor Livingood (2012) mentioned how slope was calculated. However, slope can be measured in degrees, percent (Wheatley and Gillings, 2002), or rise over run (de Smith et al., 2007), the latter of which this thesis will use.

- **Cultural features**
  - **Visibility**

As defined by Wheatley and Gillings (2000), visibility is the past cognitive acts that structured and organised the location and form of cultural features, and can be regarded as a key factor in determining why a particular site was in a particular place (Wheatley and Gillings, 2002). According to Herzog (2013b), visibility is the only social feature that is regularly considered in LCP analysis. Viewshed analysis, which explores the intervisibility of two points (observer and target points) within a landscape, commonly modelled by a DEM (Lee and Stucky, 1998), is calculated by assessing whether there is an uninterrupted straight line of sight between the two points (Lee and Stucky, 1998). The result is either a positive or negative value, coded as a 1 for a visible cell or a 0 for invisible (Wheatley, 1995). The most common viewshed analysis is the binary viewshed analysis, which shows cells both visible and invisible from one or more viewpoints (Wheatley and Gillings, 2000). For example, Ruggles et al. (1993) used a binary viewshed to analyse the distribution of stone rows in Northern Mull, Scotland. However, as stated by Ruestes Bitrià (2008), visibility is much more complex, with a binary output not reflecting the complexities of reality (Chapman, 2006), and is therefore not acceptable (Fisher, 1992). In order to determine locations most likely to have actually been seen, Ruestes Bitrià (2008) utilises cumulative viewshed, first proposed by Wheatley (1995), which sums individual binary viewsheds and results in a raster that indicates the number of times a cell is seen from the observer points (Wheatley and Gillings, 2002). In addition, Rahn (2005) investigated the link between Iron Age broch sites and visibility, finding that the LCP based on visibility coincided with the path of least resistance, suggesting that the location of broch sites were either chosen to make travel between sites as visible as possible, or to make the easiest route, whilst ensuring they were also exposed to outside observation. Nonetheless, Wheatley and Gillings (2002) note that cumulative viewshed analysis is prone to edge effects, which leads to underestimating the viewshed towards the edge of the study region. For instance, Madry and Rakos (1996) attempted to replicate segments of an Ancient Celtic road in the French Arroux River Valley by combining slope and a cumulative hillfort viewshed. However, van Leusen (1999) reflects that no account was taken to minimise the edge effect, and so the visibility values are incorrect and the conclusion that the roads were highly visible is unsupported. Furthermore, there are criticisms that viewshed analysis is a coarse representation of the sensory experience that is characterised by variability, particularly over distance (Trick, 2004). Therefore, an alternative method is the Higuchi viewshed, developed by Higuchi and Terry (1983), and demonstrated by Wheatley and Gillings (2000). The Higuchi viewshed demonstrates the distance-related property of clarity by classifying a visible area into three bands based on the visual appearance of standard objects (van Leusen, 1999). For example, Trick (2004) used Higuchi viewshed to determine that settlement mounds were positioned to give occupants a high level of vision quality. In addition, Ruestes Bitrià (2008) utilised Higuchi viewsheds and delineated four visual bands based on distance from a hillfort, noting that Higuchi viewsheds intend to show regions that might have been consistently visible, and therefore, effectively controlled.

2.3.3 How will costs be measured?

According to Herzog (2010, p.375), the cost function is "the backbone to any archaeological least-cost analysis", with Kantner (2012) stating that it is arguably the most important component of a successful cost-path analysis. A cost function allows for the calculation of the cost of each move from a raster cell to its neighbour

(Herzog, 2014a). Although there any various cost functions available (Kantner 2004; van Leusen, 1999; Wheatley and Gillings, 2002), there has been little work in evaluating which ones best model real human movement (Kantner, 2012). Nonetheless, there are two types of cost defined in cost paths: isotropic and anisotropic (Conolly and Lake, 2006; Wheatley and Gillings, 2002).

- **Isotropic Cost**

Isotropic cost functions assume that travel across a surface is neither benefitted nor hindered by the directionality of movement (Taliaferro et al., 2010), with Herzog (2010) listing that vegetation, large rivers, and visibility are typical isotropic costs. For example, the cost due to land cover is usually the same irrespective of the direction of travel: vegetation offers the same resistance whether the direction of travel is north or south (Conolly and Lake, 2006). Kantner (2012) notes that the majority of archaeological LCP analyses apply isotropic costs, assuming that travel cost across a landscape is isotropic. For instance, Rissetto (2012) sums the slope values for each cell situated between two points in order to derive a cost surface that represents the cost of travelling in a landscape. Furthermore, Siart et al. (2008) used slope as a proxy of cost in their study of Bronze Age communication paths in Central Crete. However, these are not realistic representations for the cost of movement (Surface-Evans and White, 2012), as the direction of movement across a cell becomes important: the effort of traversing a slope depends on the direction (Herzog, 2014a), with walking downhill being generally easier than walking uphill (Surface-Evans and White, 2012). For example, Kantner (2012) and Vermeulen and Antrop (2001) used slope as a proxy for cost, finding that the predicted roads were questionable and unreliable, respectively. Therefore, anisotropic cost functions have been developed (Kantner, 2012).

- **Anisotropic Costs**

Unlike isotropic costs, which take no account of the direction of movement (Wheatley and Gillings, 2002), anisotropic cost algorithms are dependent on the direction of movement (Herzog, 2013b), with the cost of travelling from point A and B not being equal to the cost of travelling from B to A (Herzog, 2010; Kantner, 2004). For example, the maximum cost of travelling across a cell is likely to be when walking uphill in the direction of the steepest slope (Conolly and Lake, 2006). Another example of anisotropic cost is travelling by boat on a river- travelling downstream is easier than upstream (van Leusen, 2002).

According to Herzog (2013a), slope is anisotropic, with the direction of movement playing an important role. Furthermore, Herzog (2010) states that slope is so important that sometimes the term anisotropic costs actually refers to costs based on slope, as is done in Conolly and Lake (2006). Nearly all archaeological studies applying LCP analysis are slope based (Herzog, 2010), with the anisotropic cost functions calculating the difficulty of moving between cells in relation to the cost in terms of time or energy when walking (Güimil-Fariña and Parcero-Oubiña, 2015; Herzog, 2010). Perhaps the best-known and most widely used anisotropic cost function in archaeological LCP analysis is Waldo Tobler's (1993) 'Hiking Function' (Gorenflo and Gale, 1990; Güimil-Fariña and Parcero-Oubiña, 2015; Wheatley and Gillings, 2001). This function allows for the assessment of time necessary to traverse a surface and takes into account up-slope and down-slope momentum (Kantner, 2004; Tobler, 1993). Although the 'Hiking Function' is based on empirical data published by Imhof (1950), which Herzog (2014a, p.232) states is "not based on sound scientific data", it is more appropriate for LCP analysis than using slope as a proxy for cost (Herzog, 2014a). Furthermore, Aldenderfer (1998) records that the calculated walking speed using the 'Hiking Function' corresponds well with recorded instances of modern and ethnographic rates of travel. For example, Verhagen and Jeneson (2012) applied the 'Hiking Function' to generate fairly direct LCPs.

Another anisotropic cost function to estimate the time taken to cover a route is the modified Naismith's rules (Langmuir, 1984), which is derived from the nineteenth-century Naismith's Rule for walking times (Naismith, 1892). For example, Ullah and Bergin (2012) used the modified Naismith's rule, which is now implemented as part of the GRASS GIS r.walk procedure (Márquez-Pérez et al., 2017), to calculate the walking time for their agent-based model. However, as reflected by Herzog (2010), the function is not intuitive because it includes a large jump in cost when travelling downhill.

Lastly, Márquez-Pérez et al. (2017) developed a 'Modified Hiking Function, which combines MIDE (París Roche, 2002), a method to calculate walking hours for an average hiker with a light load (Márquez-Pérez et al., 2017), and Tobler's 'Hiking Function' (Tobler, 1993). Using the new function, Márquez-Pérez et al. (2017) reported that it represented an improvement over the methods developed to date, and suggested that the function could be included as part of the algorithms used in optimal route analysis. However, this has yet to be done.

In contrast to the functions that estimate the time taken to traverse a surface, several functions are available that derive the energetic costs of movement (Kantner, 2012). For example, Ejstrud (2005, p.138) used the Pandolf function based on laboratory evaluations of human movement (Pandolf et al., 1977), which takes into account the weight of an unclothed person, the load carried by the person, the speed of walking, and the terrain in which the person is in (Kantner, 2012), finding that it better predicted roads in ancient Crete compared to Tobler's 'Hiking Function' (1993) "because it uses information on terrain, not only on slope". However, as reflected by Kantner (2012), many archaeological studies are not able to take advantage of the Pandolf function due to the number of variables that would be unknowable, such as walking speed of pedestrians, which Rademaker et al. (2012) assumes is constant irrespective of slope and terrain in their study of paleoindian sites in Peru. Furthermore, Herzog (2013a) reports that the function is based on experiments with a slope range of 0 to 12%, which means that the function is only appropriate for moderately ascending terrain, and concludes that the Pandolf function does not seem appropriate for archaeological LCP analysis (Herzog, 2014b).

An alternative energy cost function for modelling pedestrian movement is that proposed by Herzog (2010). Based on the function developed by Minetti et al. (2002), who measured the energy expended by ten runners walking and running at various speeds on a treadmill at different slopes, the sixth degree polynomial approximates the energy expenditure values found in Minetti et al. (2002), but eliminates the problem of unrealistic negative energy expenditure values for steep downhill slopes.

- **Combining Costs**

Cost for traversing a landscape often consists of two components: anisotropic cost (slope) and isotropic cost (Herzog, 2010). Different methods have been used to combine several cost components (Herzog, 2013b), however as reflected by Verhagen and Jeneson (2012), there are serious questions posed about how to combine slope with other cost parameters. For instance, Fiz and Orengo (2008) added slope values and a wetness factor by dividing each factor by its maximum value. However, this method depends on the maximum value, which is liable to change with different study area boundaries (Herzog, 2010), and limits the ability for comparability between studies (Herzog, 2014b). Similarly, Fovet and Zakšek (2014) suggested that slope and visibility should be combined by addition, stating that theoretically there is no dependency between the two parameters, with visibility being no more important on a steep slope than on a flat terrain. In contrast, Rahn (2005) chose multiplication over addition when combining slope and visibility, as the multiplication relationship would avoid confounding high visibility with high topographic friction. In addition, Zakšek et al. (2007) multiplied slope and visibility, with Herzog (2010) remarking that multiplication is simple and more realistic than adding, whilst avoiding negative cost values (Herog, 2013b).

2.3.4 Software used to perform the analysis

LCP analysis has been implemented in GIS software, including ArcGIS and GRASS (Surface-Evans and White, 2012), with Rahn (2007) stating that it is no longer necessary to write a specialised program as the functionality is built into the package. However, this has led to many studies using the default settings to calculate the LCP, unaware of alternatives and methodological issues (Herzog, 2014b). For instance, Conolly and Lake (2006) note that there are different cost accumulation algorithms for the generation of the LCP. According to Herzog and Posluschny (2011), the spreading algorithm in GIS software is typically based on Dijkstra's algorithm (Dijkstra, 1959). However, as stated by Herzog (2013b), Dijkstra's algorithm is implemented differently in different LCP software, leading to significant variations in LCP analysis results. For example, Gietl et al. (2008) compared LCP results using ArcGIS, GRASS GIS and IDRISI, finding that it was impossible to recreate the same or similar results from one software with another, even when the same data and weightings were used.

In addition to the accuracy of the LCP calculation depending on the correct implementation of Dijkstra's algorithm, the number of neighbouring cells considered is important (Herzog and Posluschny, 2011; Harris, 2000) (Figure 1, overleaf).

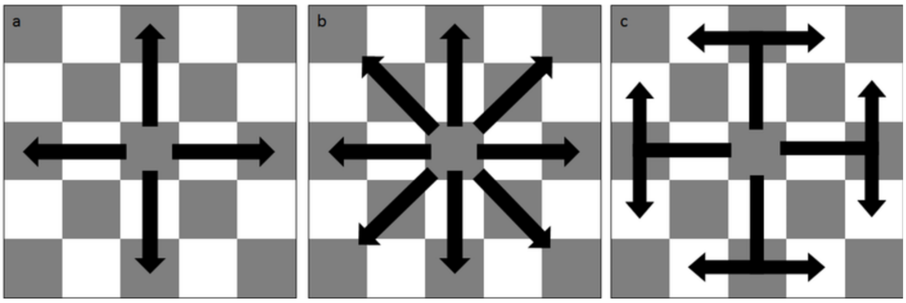


Figure 1: Neighbouring cells considered using four (a), eight (b) and sixteen (c) directions (Ahlrichs et al., 2016)

van Leusen (2002) notes that cost accumulation is usually performed using a 4-neighbour or 8-neighbour spreading algorithm. However, this can result in incorrect accumulated costs, caused by what Harris (2000) called ‘elongation error’ (i.e., the difference in length between the LCP and the optimal straight line route). This error is caused by the conversion from raster cells to a vector graph, in which Dijkstra’s algorithm is designed for (Herzog, 2014a). For example, the LCPs created by Nolan and Cook (2012) using ArcGIS were limited to movement in 8 directions. Due to this, the LCPs deviated from the optimal straight line, instead moving in cardinal directions (N, E, S, W), and switching to sub-cardinal directions (N-E, S-E, etc) (Herzog, 2014a). To minimise the effect of ‘elongation error’, Harris (2000) suggests a 48-neighbour kernel, which reduces the error to below 1.4% (Huber and Church, 1985). In contrast, Herzog (2014b) states that a minimum of 16- or 24-neighbour kernel is appropriate for route construction, with Huber and Church (1985) recommending a neighbourhood of 24 cells, stating that it provides the best trade-off between accuracy and computational burden. For instance, Ullah and Bergin (2012) used GRASS GIS which supports movement in 24 directions, and therefore minimising elongation errors to 2.8% (Herzog and Posluschny, 2011; Huber and Church, 1985). However, GRASS GIS implements Dijkstra’s algorithm incorrectly, which can lead to the computed path being different than the true LCP (Herzog and Posluschny, 2011).

2.3.5 Validation of the LCP results

According to Herzog (2014a), the most important component of a LCP analysis is the validation of the results, further stating that without validation, the LCP results are “mere guesswork” (Herzog, 2013b, p.205), and purely exploratory (Herzog, 2014a). Moreover, the reliability of LCP analysis needs to be proven through comparative studies of calculated and preserved routes, without which will impose a challenge for LCP applications (Kantner, 2012). Although there is no established method for validating LCPs (Kantner, 2012), Herzog (2014a) states that comparison between the LCP and remnants of old routes is the best option, with comparison to route indicator sites such as burial mounds being the second. However, this is uncommon, with most studies not including validation of the LCP results (Herzog, 2014a; Vermeulen, 2006). For instance, more than half of the case studies in White and Surface-Evans (2012) do not address validation, whilst Vermeulen (2006) reflects that many archaeological predictive models have been created and never validated at all.

Nonetheless, there are exceptions. For instance, Herzog (2014c) assessed the similarity between predicted LCPs and ancient trade routes by visual impression, stating that the differences were evident. Similarly, Güimil-Fariña and Parcero-Oubiña (2015) followed a more formal procedure suggested by Goodchild and Hunter (1997), which evaluates the similarity between two linear features by determining the percentage of a linear feature that lies within a buffer distance from the 'true' linear feature.

However, as noted by Herzog (2014a), there is still a need for a more objective method for testing the agreement between the known routes and the LCP results. Furthermore, the percentage obtained from the method proposed by Goodchild and Hunter (1997) is coarse and lacks the ability of determining the distribution of the linear geometric quality (Ali, 2003). Therefore, this thesis proposes the use of flow maps, which have yet to be used in the context of LCP analysis. Although flow maps are commonly used to visualise linear movement (Boyandin et al., 2010; Jenny et al., 2016), with the line thickness indicating the quantity of movement (Dent et al., 2009), the line thickness in this case will represent the distance from the predicted LCPs to the known Roman roads, with Tufte (1983, p.40) commenting that adding spatial dimensions to the design of the graph is "especially effective", as well as allowing for differences in magnitude of a value to be easily seen, whilst adding very little map clutter (Phan et al., 2005).

2.4 Summary

Through reviewing LCP analysis literature, the following gaps were identified:

1) DEM related issues when doing LCP analysis are rarely addressed. Therefore, this thesis will evaluate multiple resolution DEMs and their effect on the computed LCP.

2) Watercourses can affect movement through a landscape both positively and negatively, however LCP studies often exclude this from the model. Therefore, to better reflect the real life landscape, watercourses will be included.
3) The positional accuracy of locations used in LCP analysis is often not recorded. Therefore, this thesis will detail the positional accuracy of the locations used.
4) Many LCP analysis studies fail to evaluate the effects of slope calculation on LCP computation. Therefore, LCPs based on multiple slope calculations will be evaluated.
5) Visibility in previous LCP analyses are too simplistic and don't reflect the complexities of reality. Therefore, the Higuchi viewshed will be utilised in the LCP computation.
6) In LCP analysis, there are multiple anisotropic cost functions that can be used. Therefore, the LCP results using different cost functions based on time and energy will be assessed and evaluated.
7) Previously used software in LCP analysis is limited in its functionality, with settings leading to error-prone LCPs. Therefore, custom software will be used to allow for greater flexibility.
8) The validation of LCP results is uncommon, with the need for a more objective method to test the accuracy of the LCP. Therefore, the LCPs will be validated through previously used methods, as well as employing flow maps, which has yet to be applied in the context of LCP analysis.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

Using the gaps identified in the previous chapter, the data and computational needs were established. From this, this chapter outlines the four study areas chosen to conduct the study, the data needed in order to create the least cost path models, and the software used to compute the LCPs. Furthermore, the methodological assessment of the LCP results is outlined, as well as the methods used to validate the accuracy of the predicted LCPs.

3.2 Study Overview

In order to assess the suitability of LCP analysis for predicting of Roman roads, three study areas were chosen within the Highland zone (The Gask Ridge; The Stanegate; and Tomen Y Mur – Caer Gai), and one within the Lowland zone (Benenden – Canterbury) (Figure 2). By choosing a greater number of study areas within the Highland zone, the environmental determinism of LCP analysis can be assessed.

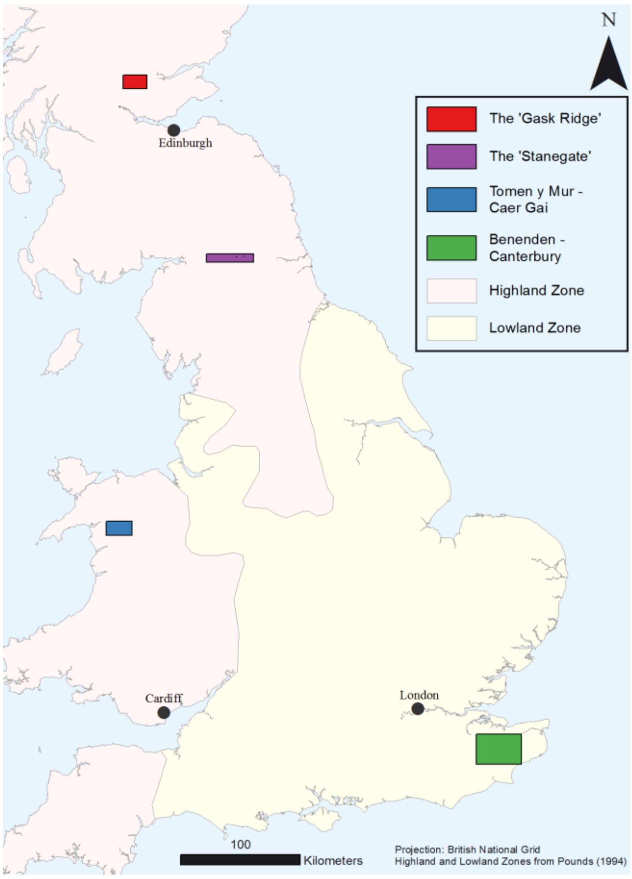
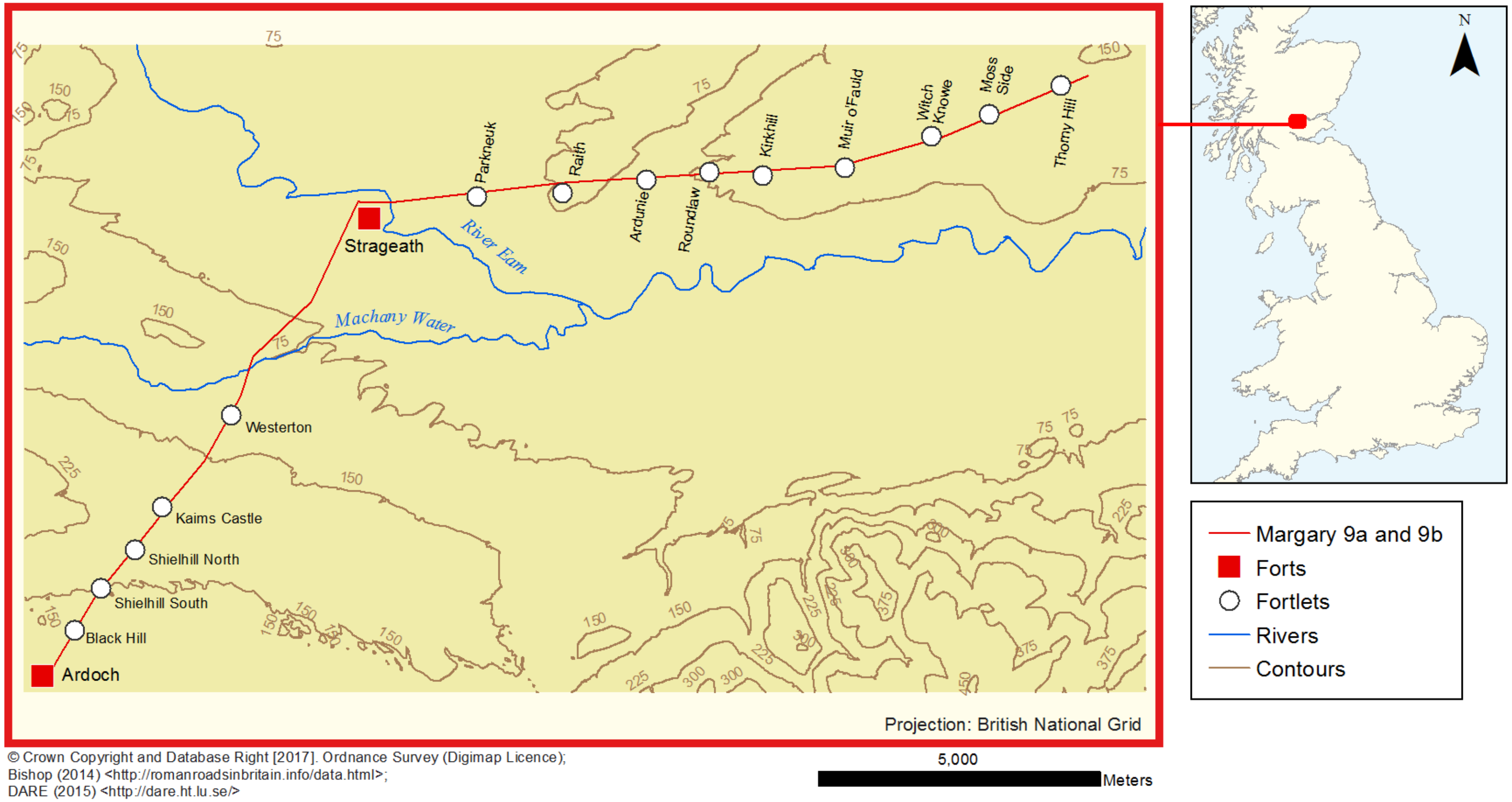


Figure 2: Overview of study areas and the Highland and Lowland zones of Roman Britain

3.3 Study Areas

3.3.1 The Gask Ridge Study Area

The Roman Gask Ridge system is a line of forts, fortlets and timber watch towers situated along a Roman road that runs into Perthshire, northern Scotland (Roman Gask Ridge Project, 2017; Breeze, 2011). Known as Margary 9a and Margary 9b (Margary, 1973), the road from Ardoch to Bertha, which has been identified in the field from Ardoch to just past Thorny Hill (Figure 3, overleaf), served as the northern limit of permanent occupation in Scotland (Hanson and Maxwell, 1986), with the forts and fortlets assigned as Flavian (85-90 AD) in date (Breeze, 1982). According to CFB (2016), the road performed a purely military function, keeping the forts supplied (Hoffman, 2013), whilst the fortlets controlled the movement along and across the road (Hanson and Maxwell, 1986), allowing for the army to see what was happening (Breeze, 1982).



© Crown Copyright and Database Right [2017]. Ordnance Survey (Digimap Licence);
Bishop (2014) <http://romanroadsinbritain.info/data.html>;
DARE (2015) <http://dare.ht.lu.se/>

Figure 3: The Gask Ridge study area

3.3.2 The 'Stanegate' Study Area

Following the abandonment of the 'Gask Ridge' in the early second century (c. 105 AD), the Stanegate, which is the natural gap formed by the rivers of Tyne and Irthing, became the most northerly line of military stations in Britain (Breeze, 1982), with fortifications being rebuilt and re-garrisoned in AD 105 (Roman Britain, 2017b). According to Hodgson (2000), the forts, which ran from Corbridge to Carlisle, were arranged along the military line of the Roman road known as Margary 85a and 85b (Margary, 1973), or more commonly the Stanegate military road. After AD 105, fortlets were built between the forts, which Hanson and Maxwell (1986) state indicates the increasing importance for surveillance and the control of movement through the area. As identified by Margary (1973), the Stanegate military road is visible in the field from the River North Tyne to Bootby fortlet (Figure 4, overleaf).

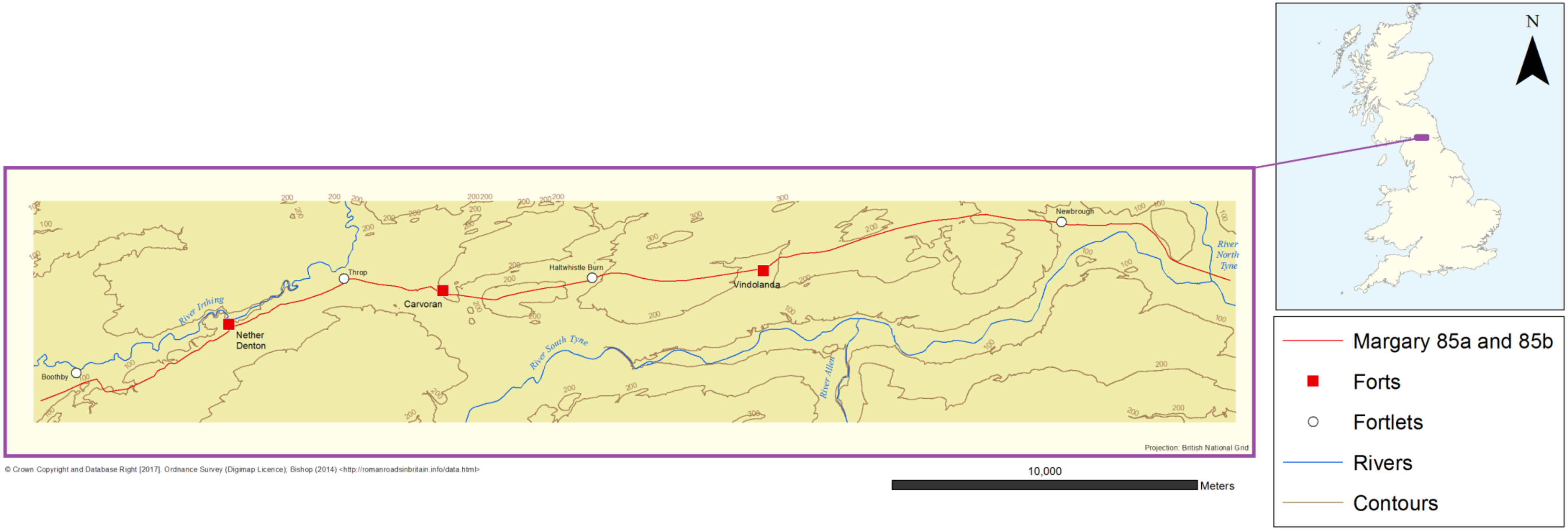


Figure 4: The Stanegate study area

3.3.3 Tomen Y Mur – Caer Gai study area

Forming part of the Roman road that connected the fort of Segontium at Caernarfon, North Wales, to the Roman fort in Caer Gai, North Wales, the Tomen Y Mur to Caer Gai road (Figure 5, overleaf) has been identified in the field, and is known as Margary 68 (Margary, 1973).

According to The National Museum of Wales (2007), the Roman fort of Segontium was built in AD 77 as a result of the campaigns in North Wales, and occupied a key position in the Roman military network. Similarly, the Roman forts at Tomen Y Mur and Caer Gai were built in AD 77/78 (Gwynedd Archaeological Trust, 2005; Roman Britain, 2017a), with the Roman fort at Caer Gai sited at a strategic point in the road system (Wiles, 2007). Once Wales was secured in AD 78 (Davies, 1990), the road network was developed, linking the forts, and facilitating the movement of troops and supplies (Cadw, 2011).

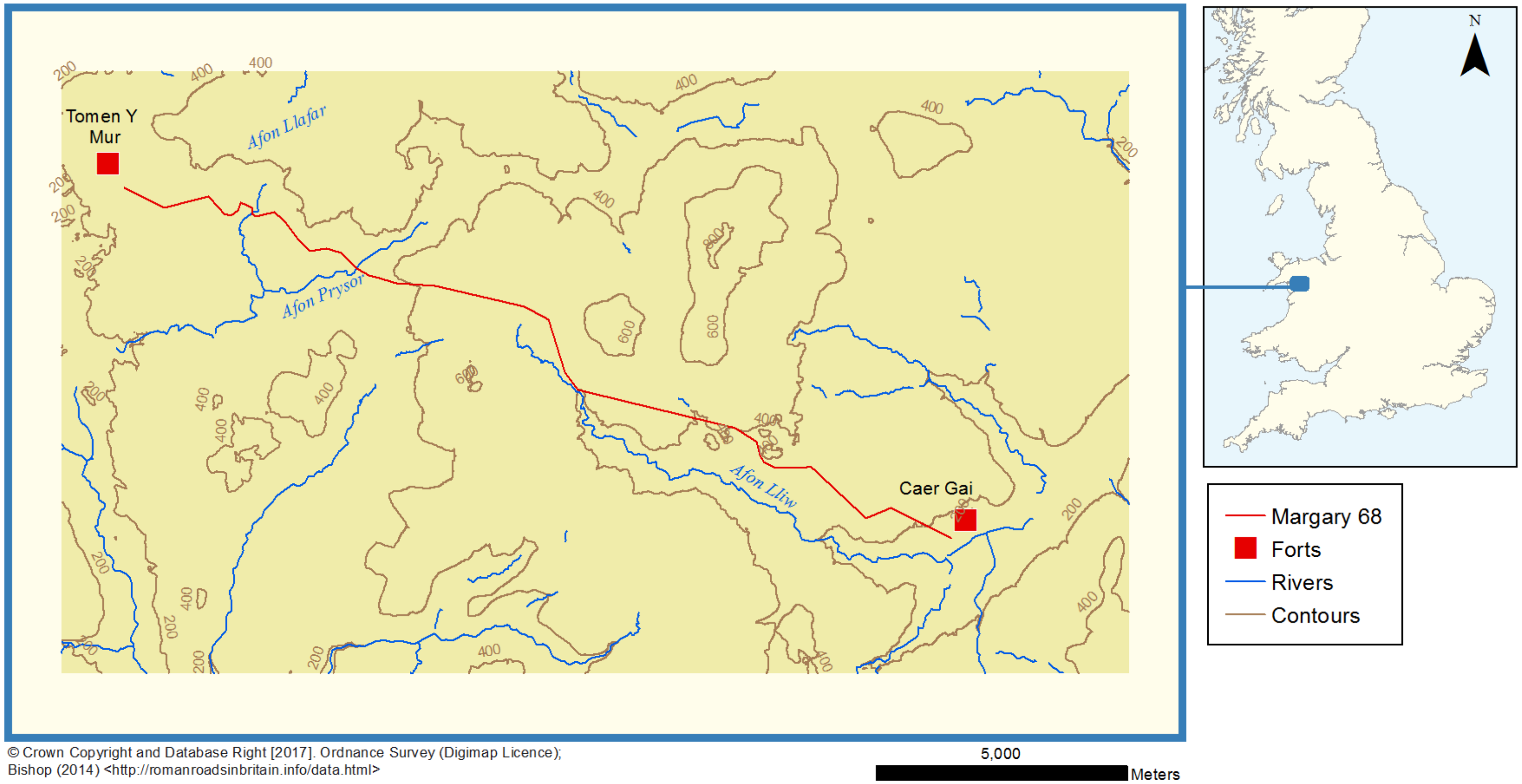


Figure 5: Tomen Y Mur – Caer Gai study area

3.3.4 Benenden - Canterbury study area

According to Margary (1973), the Benenden – Canterbury Roman road, also known as Margary 130 (Margary, 1973), is the eastward branch from the ironworking districts in the Weald, South East England; and was primarily commercial in its purpose (Figure 6, overleaf), with two ironworking sites at Ashford used to process ores into workable metals (Lawrie, 2004), as well as the Roman settlement at Benenden being near two road junctions (Pollard and Aldridge, 2008) and WestHawk Farm, Ashford settlement being significant for communication (ABC, 2017; Swat Archaeology, 2010). Built in the early 3rd century, the road offered land-borne transportation, and assisted in the spread of iron products to new markets (Cleere, 1981). Furthermore, the roads offered a safer transport option than sea, as attacks from pirates and raiders became more prevalent from the beginning of the 3rd century (Cleere and Crossley, 1985).

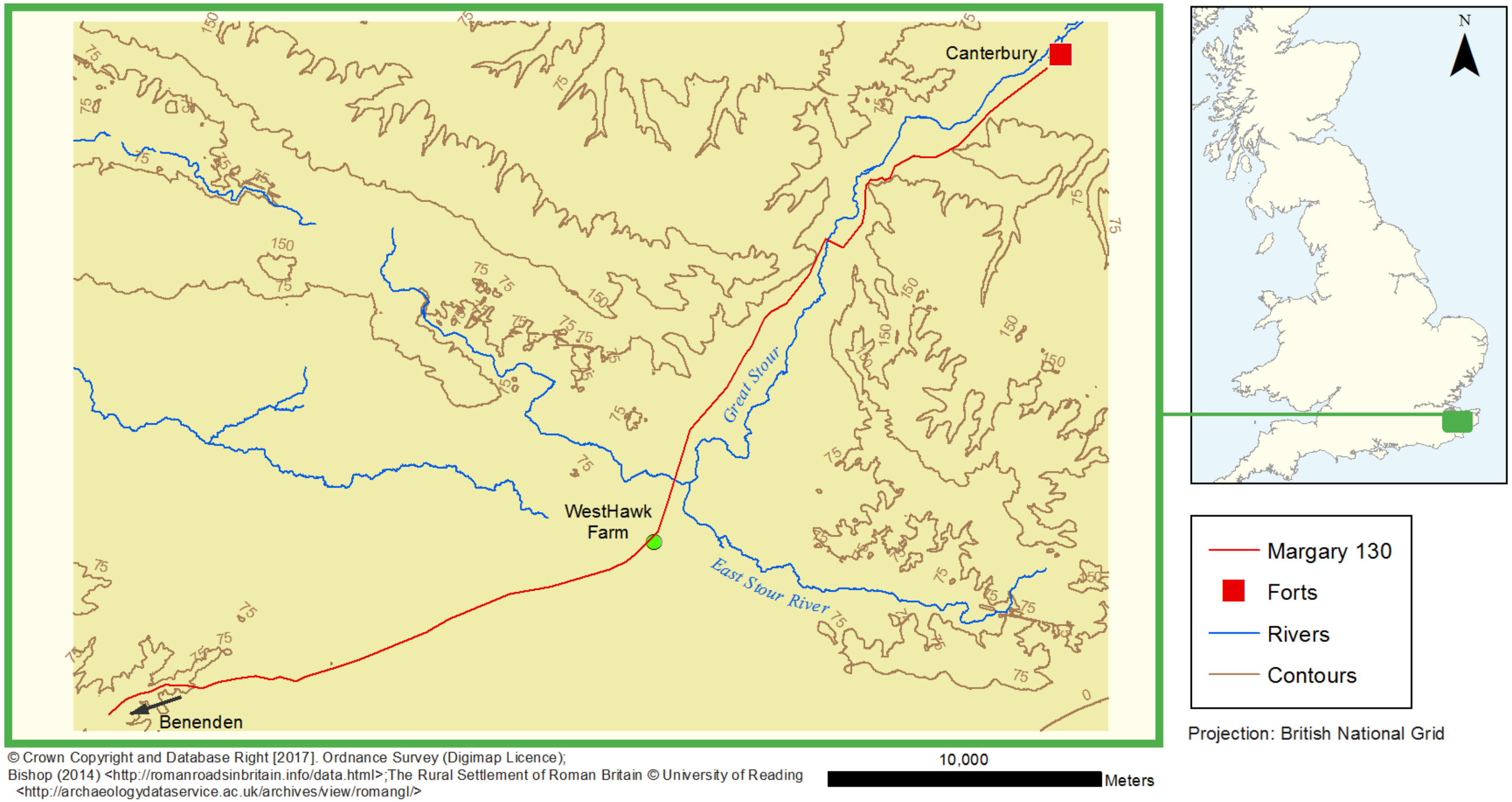


Figure 6: Benenden - Canterbury study area

3.4. Data

- **OS Terrain 5 DTM**

Described as a mid-resolution data terrain model (DTM), the OS Terrain 5, which is produced by the Ordnance Survey (OS), has a resolution of 5 metres, and was designed to be interoperable (Ordnance Survey, 2017b). Furthermore, the OS Terrain 5 is the highest resolution available from the OS for areas with no LIDAR coverage, and has an accuracy level greater than 2m RMSE (Ordnance Survey, 2017a). In order for the DTMs to cover the study areas, the 5km by 5km tiles ordered through http://digimap.edina.ac.uk/ were merged into a new raster using ArcGIS.

- **Shuttle Radar Topography Mission (SRTM)**

The SRTM data elevation model (DEM), available from the US Geological Survey (USGS, 2017a), has a spatial resolution of 1 arc seconds (~30m) (USGS, 2017b). The data was converted from WGS84 projection to the British National Grid, resulting in a final resolution of 24m. As noted by Rademaker et al. (2012), SRTM provides a more accurate representation of the landscape compared to similar resolution DEMs. Furthermore, Becker et al. (2017), in their investigation of the influence of DEMs on cost distance modelling, found that SRTM is well suited for this purpose, and has been used frequently in LCP analysis (Alexander et al., 2016; Rademaker et al., 2012; Siart et al., 2013; Taliaferro et al., 2010).

- **Margary's Roman Britain Road Network**

The digitised version of Margary's Roman Britain road network was made freely available in conjunction with the release of *The Secret History of the Roman Roads in Britain* (Bishop, 2014), and was downloaded from http://romanroadsinbritain.info/data.html. According to the Digital Atlas of the Roman Empire (DARE, 2015), the estimated accuracy of the digitised version is 20 metres. Due to the file format being KML, it was converted to a shapefile and projected to the British National Grid using ArcGIS. Within the shapefile, there contained additional layers such as medieval timber castles. Subsequently, a layer was created consisting of only the line and point features that corresponded to Margary's Roman roads and pre-Hadrianic Roman forts (Figure 7), which ensures that all the forts within the study areas are kept. Due to Margary (1973) recording the certain and probable course of the Roman roads, the roads were clipped to where the roads are marked as certain, to ensure that the roads are known in their location and have been identified in the field. The end vertices of the chosen Roman road in each study area were then converted to points using the Vertices to Points tool in ArcGIS. These points were used as the origin and destination points in the LCP analysis.

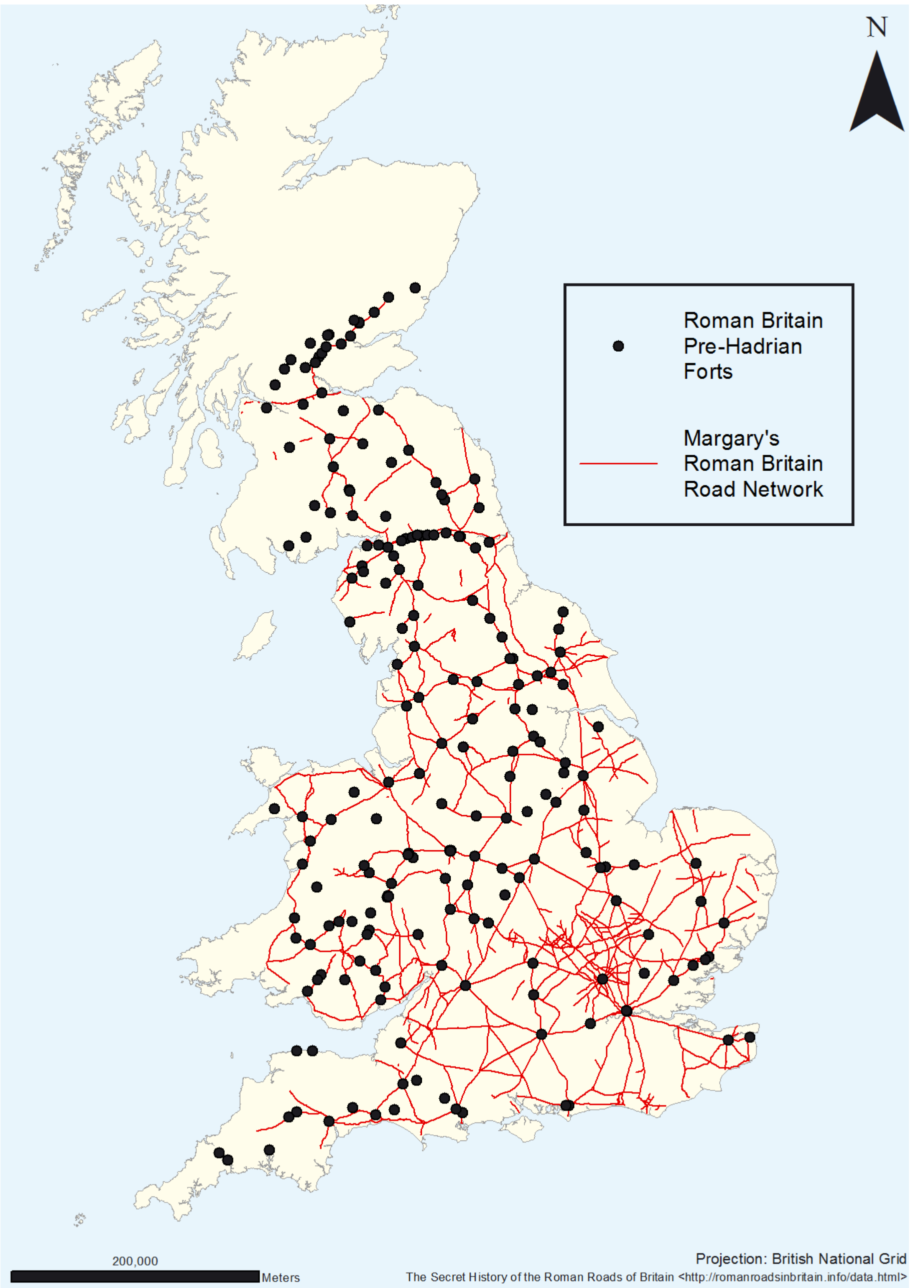


Figure 7: Margary's Roman Britain road network and location of Pre-Hadrian forts digitised by Bishop (2014)

- **Archaeological Sites**

Although the digitised version of Margary's Roman Britain road network included many fortlets, some were missing within the study areas. In order to identify the location of the missing fortlets, the *Digital Atlas of the Roman Empire* was used (DARE, 2015). From this, the locations of the fortlets were input into a CSV file (*Appendix A*), and imported into ArcGIS. As the locations were in WGS84 coordinate system, they were projected to the British National Grid. Like the digitised version of Margary's Roman Britain road network, the estimated accuracy is 20 metres (DARE, 2015).

- **Ordnance Survey Open Rivers**

The linked watercourse network of Great Britain was produced by Ordnance Survey (OS), and was downloaded from http://digimap.edina.ac.uk. The linked network is a topological two-dimensional network that represents the approximate alignment of the watercourse (Ordnance Survey, 2016). In order to reduce the number of watercourses, only those with river in their name were kept (Figure 8, overleaf).

Figure 8: Watercourses identified as rivers in Great Britain

The network was clipped to the study areas using the Clipping tool in ArcGIS. The locations where the rivers intersected Margary's Roman Britain road network were buffered by 50m and 300m for the OS Terrain 5 and SRTM DTM respectively, and removed from the watercourse via the difference tool, resulting in a river network with gaps representing bridges, which were commonly used to cross rivers in Roman Britain (Bishop, 2014). Due to this, the LCPs are forced to cross the bridges, and follow the method suggested by Herzog (2010; 2012). The Euclidean distance tool in ArcGIS with a maximum distance of 30m and 180m for the OS Terrain 5 and SRTM DTM was used on the watercourse network. This adding of additional cells to the watercourse network follows that recommended by Conolly and Lake (2006).

Furthermore, the distance of 30m and 180m, which are greater than the maximum distance of connected neighbouring cells ensures that the rivers act as barrier to movement, and eliminates the possibility of the rivers being breached, which van Leusen (2002) states is a potential problem when allowing movement in 16 directions (Figure 9).

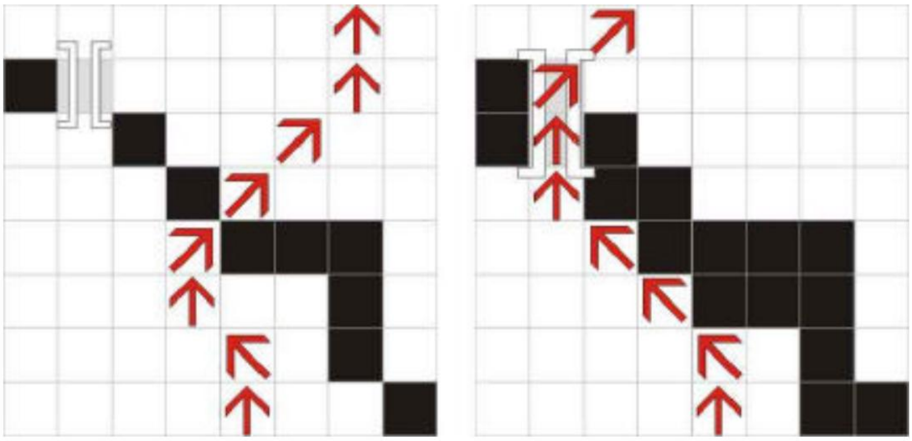


Figure 9: The LCP 'jumping' a one-cell-wide cost barrier by using diagonal movement (left); widening the cost barrier forces the LCP to cross points such as bridges (right) (van Leusen, 2002, p.16.6)

Lastly, the rivers were reclassified to a value of 0, whilst values of 1 were allocated to the rest of the study area (Figure 10, overleaf).

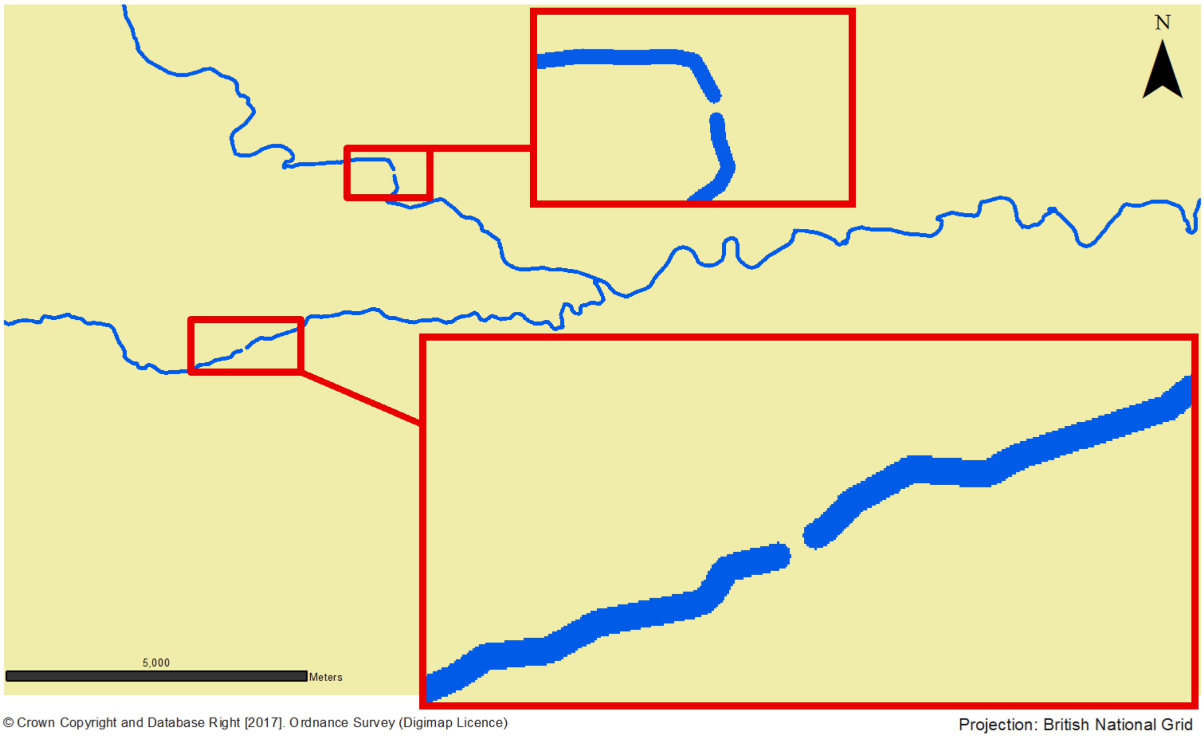


Figure 10: Reclassified rivers with a value of 0 (blue) in the Gask Ridge study area with 5m resolution. Insets showing the gaps in the watercourse signifying bridges

- **Visibility**

The visibility method used in this study was the Higuchi viewshed, as detailed in Wheatley and Gillings (2000), which had yet to be used in the context of LCP analysis. The Higuchi viewshed was used as the method classifies visible areas based on the visual appearance of objects (van Leusen, 2002). Similarly, as noted by Ruestes Bitrià (2008), the Higuchi viewshed identifies particular regions that are more visible, and so can be controlled more easily, which has been stated as a key factor in the function of the Roman roads found in two of the study areas examined in this thesis: namely, the Gask Ridge and the Stanegate.

Following the process outlined by Wheatley and Gillings (2000), frequency viewsheds were created using fortlets as the observer points, with the OS Terrain 5 acting as the input surface raster. As noted by Woolliscroft (2001), the fortlets were 10m in height, and so an observer offset of 10m was added to the fortlets altitude. The viewsheds were then reclassified to create binary viewsheds. Distance layers from the fortlets were then created, which encodes each cells with a value that is equal to the distance away from the fortlets. Subsequently, the distance layers were reclassified into short, middle and long-distance zones. As the formula proposed by Higuchi (1983) was developed using the forested landscapes of rural Japan (Ruestes Bitrià, 2008), as well as the trees surrounding Roman roads being cleared as to facilitate a clear view (CFB, 2016; Knapton, 1996; Wacher, 2000), the four visual ranges proposed by Ruestes Bitrià (2008) were utilised: the first zone represents 1km from a fortlet. According to Fisher (1994), the clarity of visibility at this distance can be considered perfect. Therefore, visual control could have been excellent; the second zone is 3km. At this radius, visibility decreases, however it would still be possible to see features with significant clarity, with Ruestes Bitrià (2008) stating that it would still be possible to distinguish a group of people walking along a pathway; the third zone is 6km, which is when clarity begins to decay significantly (Ruestes Bitrià, 2008); whilst over 6km it is possible to see but not be sure what is being seen (Ruestes Bitrià, 2008). The binary viewsheds were then used as mask to extract the distance zones that fell within the in-view areas of the binary viewsheds, resulting in a Higuchi viewshed that consisted of the four distance zones.

Lastly, the zones were reclassified based on the values calculated by Ogburn (2006), who assessed the level of visibility of cultural objects in past landscapes: 1km zone allocated a value of 6880; 3km zone a value of 3440; 6km zone a value of 1150; and over 6km a value of 57. In addition, the areas that are not visible from the fortlets were allocated a value of 1 (Figure 11, overleaf). It should be noted that Ogburn (2006) reported inversely, giving the shortest-distance zone a value of 57. However, the LCP software used in this study is based on the ease of travelling through a landscape, and so the greater number is given to the area most visible from the fortlets (i.e., the 1km zone), thus 'easier' to travel through.

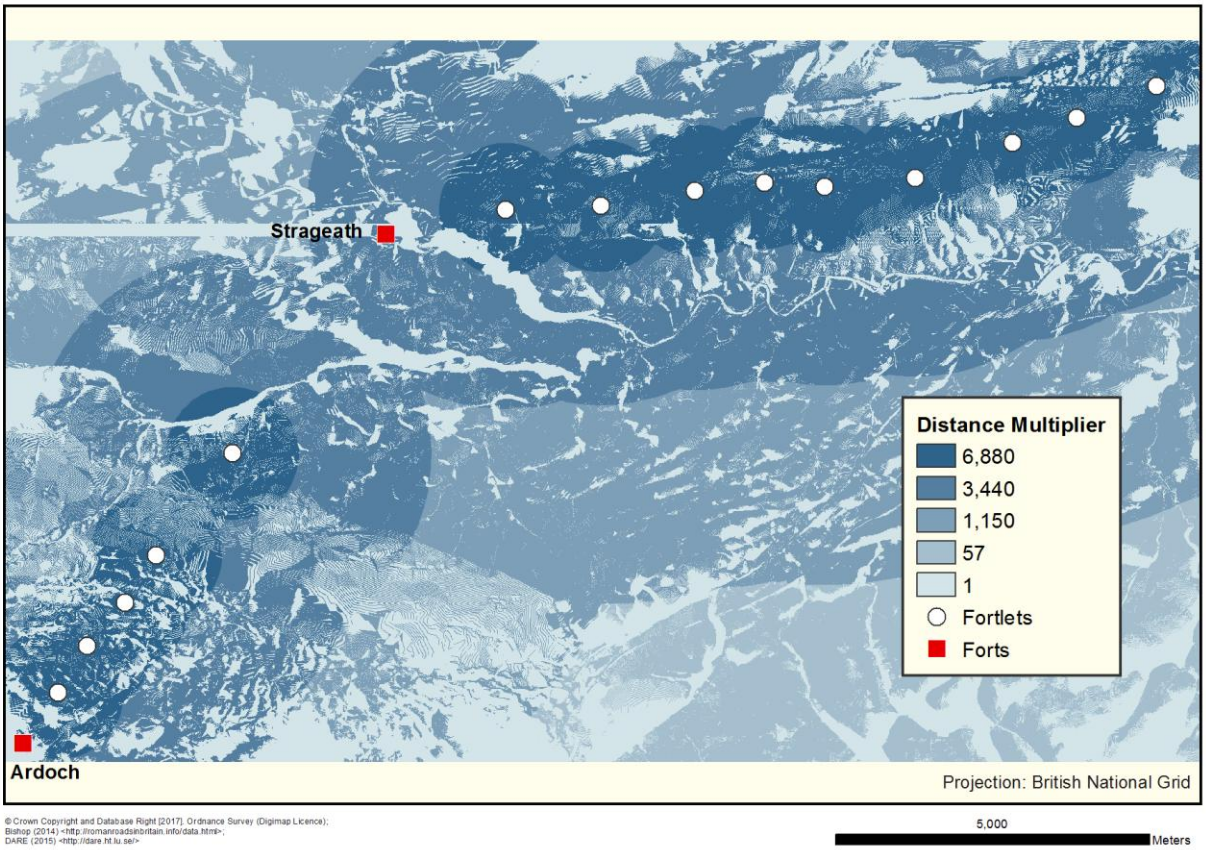


Figure 11: Higuchi viewshed cost surface for the Gask Ridge study area, showing the four distance zones and their distance multiplier.

3.5 LCP Calculation

Although LCP analysis is possible in other GIS software (e.g., ArcGIS, GRASS), the analysis was conducted within R Studio, using the freely available spatial analysis package *gdistance* (van Etten, 2017). According to van Etten (2017), *gdistance* is comparable to other software such as ArcGIS Spatial Analyst (McCoy and Johnston, 2002) and GRASS GIS (GRASS Development Team, 2017). However, *gdistance* allows for up to sixteen neighbours pattern recognition, which is in line with Herzog's (2014b) statement that a minimum of sixteen neighbours is appropriate for route construction. In addition, *gdistance* allows for greater flexibility in the calculation of cost surfaces (van Etten, 2017), which Fovet and Zakšek (2014) state is problematic when using GIS software. For instance, Fovet and Zakšek (2014) was limited to combining cost surfaces by multiplication when using ArcGIS, even though they reflected that addition was a more suitable method for their study.

- **Producing the cost surface raster** *(full code in Appendix B)*
    - **Terrain cost surface**

The cost surface raster based on slope is dependent on the differences of vertical elevation between neighbouring cells and the distance travelled between these cells (van Etten, 2017).

```
altDiff <- function(x){x[2] - x[1]} # function to calculate altitude difference between cells

hd <- transition(dtm_raster, altDiff, directions, symm=FALSE) # transition values of neighbouring cells

# dtm_raster is the terrain raster with elevation values;
# directions can be 4,8, or 16 and denotes the number of directions by which differences in height are calculated from the centre origin cell;
# symm is TRUE for isotropic cost functions, FALSE for anisotropic cost functions

slope <- geoCorrection(hd) # difference in height between cell divided by the distance between cells
```

As the slope has been calculated between neighbouring cells, the following calculations must be limited to adjacent cells.

```
adj <- adjacent(dtm_raster, cells=1:ncell(dtm_raster), pairs=TRUE, directions)
```

The slope values are then used alongside a cost function in order to produce a cost surface that measures the cost to traverse between neighbouring cells (Herzog, 2014b). The cost functions define the effort of moving a certain distance based upon the values of a certain parameter; for instance, the slope (Nakoinz and Knitter, 2016). The cost functions used in this analysis are Tobler's Hiking Function (Tobler, 1993), which is possibly the most popular cost function in LCP analysis (Herzog, 2010), Herzog's Sixth Polynomial (2010), which avoids disadvantages of other energy-based cost functions (Herzog, 2014b), and Márquez-Pérez et al. (2017) Modified

Hiking Function, which combines the precision of the MIDE rule and the continuity of Tobler's Hiking Function (Márquez-Pérez et al., 2017).

Tobler's 'Hiking Function' (Tobler, 1993):

```
cost <- slope

cost[adj] <- 6 * exp(-3.5 * abs(slope[adj] + 0.05)) # calculates speed of movement between adjacent cells. Cost function as stated in van Etten (2017)
```

Herzog's sixth polynomial (Herzog, 2010):

```
cost <- slope

cost[adj] <- 1 / ((((1337.8 * slope[adj]^6) + (278.19 * slope[adj]^5) - (517.39 * slope[adj]^4) - (78.199 * slope[adj]^3) + (93.419 * slope[adj]^2) + (19.825 * slope[adj]) + 1.64)))
# calculates energy usage between adjacent cells. Cost function as stated in Nakoinz and Knitter (2016)
```

Modified Hiking Function (Márquez-Pérez et al., 2017):

```
cost <- slope

cost[adj] <- (4.8 * exp(-5.3 * abs((slope[adj] * 0.7) + 0.03)))
# calculates speed of movement between adjacent cells. Cost function based on Márquez-Pérez et al. (2017)
```

Watercourse Network cost surface

A transition object was created for the watercourse network cost surface, with the transition function averaging the values of neighbouring cells. This ensures that the values denoting rivers remain unchanged.

```
river_cs <- transition(river_raster, transitionFunction = mean,directions = 16,
symm=TRUE)
# neighbouring cell values are averaged
```

Higuchi Viewshed cost surface

Similarly, a transition object for the Higuchi viewshed cost surface was created, with the transition function averaging the values of neighbouring cells.

```
view_cs <- transition(view, transitionFunction = mean, 16, symm=TRUE)
# neighbouring cell values are averaged
```

Combining cost surfaces

As recommended by Herzog (2010) and Zakšek et al. (2007), the slope-based cost surface and the Higuchi viewshed cost surface were multiplied. This ensures that negative cost values are avoided (Herzog, 2013b), as Dijkstra's algorithm (Dijkstra, 1959) is designed for positive values only (Herzog, 2014b). Furthermore, the visibility values used in the Higuchi cost surface are defined as 'distance multipliers' (Ogburn, 2006, p.410), and thus are used by multiplying the slope-based cost surface with the Higuchi visibility cost surface.

Similarly, the watercourse network cost surface, which consists of a 0 value for rivers and 1 for everywhere else, was multiplied to the resultant cost surface previously calculated. This ensures that rivers continue to have a value of 0, and so continue to act as barriers to movement, whilst the rest of the cost surface remains affected due to multiplying by the value of 1.

```
combined_cs <- (cost * view_cs) * river_cs
```

To correct for diagonal cell connections, which take longer to cross than straight connections (van Etten, 2017), the function geoCorrection is used, resulting in the final cost surface raster.

```
Conductance <- geoCorrection(combined_cs)
```

Two coordinates, which denote the origin and destination of the LCP, are specified.

```
pts <- cbind(x=c(origin_x, destination_x), y=c(origin_y, destination_y))
```

The shortestPath function provided by *gdistance* (van Etten, 2017) calculates the shortest path from the origin coordinate point to the destination coordinate point, and outputs a SpatialLines object.

```
AtoB <- shortestPath(Conductance, pts[1,], pts[2,], output="SpatialLines")
```

The resultant SpatialLines object is converted to a SpatialLinesDataFrame object using the R package *sp* (Bivand et al., 2013)

```
AtoBdf <-SpatialLinesDataFrame(AtoB, data.frame(id=1:length(AtoB)))
```

The SpatialLinesDataFrame object is saved as an ESRI Shapefile using the R package *rgdal* (Bivand et al., 2016)

```
writeOGR(AtoBdf, dsn="", layer="LCP" ,driver="ESRI Shapefile")
```

3.6 Methodological assessment

In order to assess the effect of the number of neighbouring cells used in the LCP analysis, which van Etten (2017) states may change the accuracy of the LCP calculation, the above methodology was repeated multiple times for the ‘Gask Ridge’ study area, changing the number of directions from 4,8,and 16 each time, whilst using Tobler's Hiking Function. The Gask Ridge study area was chosen due to its purely military function, which ensures that the minimisation of distance between two locations was important (Davies, 2002; Herzog, 2013b; Poulter, 2010), whilst the Tobler's 'Hiking Function' (Tobler, 1993) is the best known cost function in LCP analysis (Wheatley and Gillings, 2001), and is most comparable with other studies (e.g., Güimil-Fariña and Parcero-Oubiña, 2015; Herzog, 2013b; Surface-Evans, 2012; Verhagen and Jeneson ,2012; Verhagen et al., 2014). According to Herzog (2014b), the worst case distance between the optimal straight line route and the LCP is a more appropriate performance indicator than the elongation error as the LCP is calculated from an non-uniform cost surface, and will often be longer than the true optimal straight line path (Figure 12). Therefore, the distance between the optimal straight line and the LCPs generated when using a different number of directions were compared. Furthermore, the accuracy of the LCPs generated using the OS Terrain 5 and SRTM DEM were compared and evaluated.

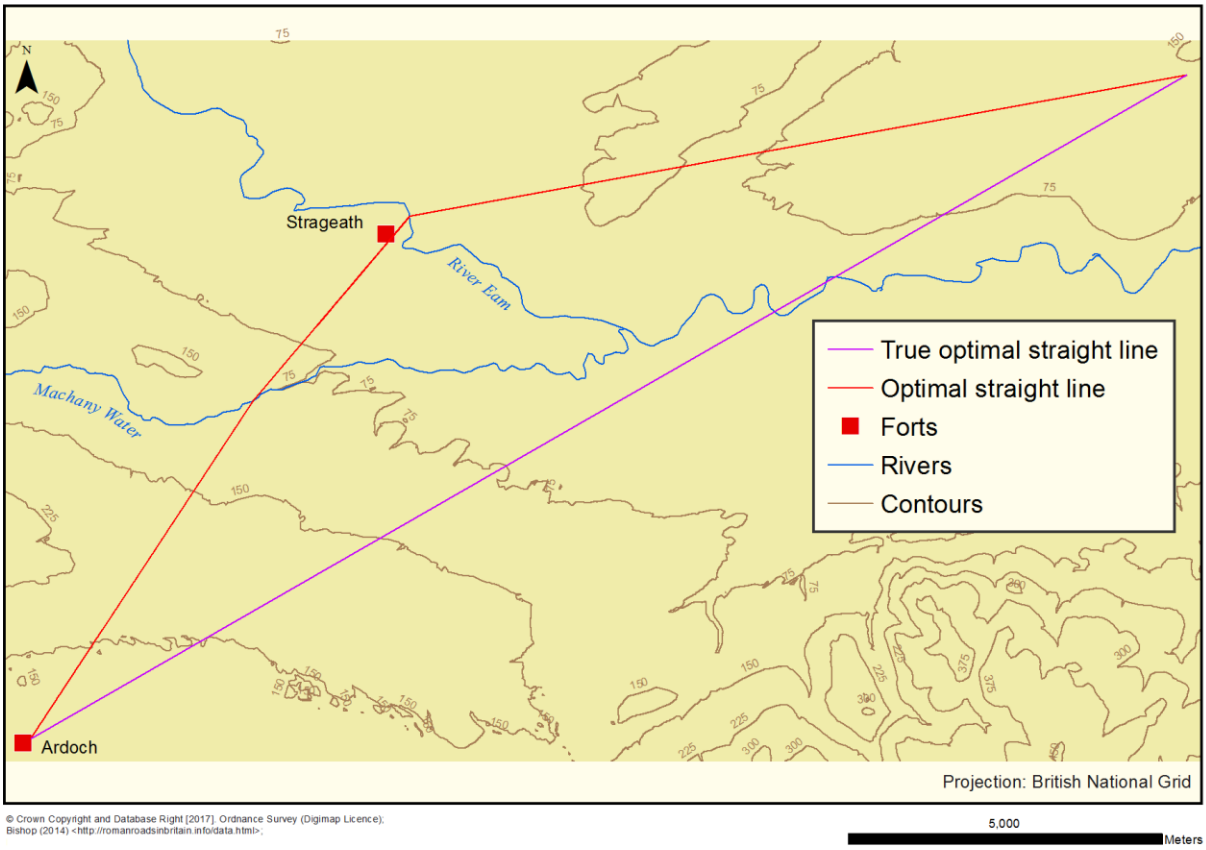


Figure 12: 'True' optimal straight line and the optimal straight line that incorporates the river crossings

Once the number of neighbouring cells that bore the most accurate LCP calculation was determined, the LCP analysis was once again repeated for the 'Gask Ridge' study area, incorporating the other two cost functions, whilst keeping the number of neighbouring cells the same.

The most accurate cost function, as well as the most accurate number of neighbouring cells, was then used in the LCP analysis to calculate the LCP for the other three study areas. Similarly, the Gask ridge and Stanegate LCP calculations were also computed with the incorporation of the Higuchi viewshed. This was done as surveillance and the desire for control of the roads in the Gask ridge and the Stanegate has been stated as an important factor in the development of the roads.

3.7 Validating the predicted Roman roads

The validation of predicted LCP was accomplished by comparing the Roman roads from Margary's Roman road network with the predicted LCP, which Herzog (2014a) states is the best option for validation. Due to the 20m estimated accuracy of Margary's Roman road network, the known Roman roads were buffered by 20m. This ensures that there is a 100% probability of the known Roman roads being within the buffer zone (Shi, 2010), and follows the method suggested by Goodchild and Hunter (1997) when dealing with spatial uncertainty.

Following Güimil-Fariña and Parcero-Oubiña (2015) who also used the method suggested by Goodchild and Hunter (1997), a buffer of 250m, 500m and 1000m was created from the previously 20m buffered Roman roads. Although the buffer distances are arbitrary, they coincide with those chosen by Güimil-Fariña and Parcero-Oubiña (2015) and Schild (2016), as well as being factors of the DEM cell size, which Schild (2016) recommended. From this, the percentage of the LCP that lay within the buffer distances could be calculated, which corresponded to the entire study area. However, as previously stated, the results from this method are coarse. Therefore, flow maps were utilised, which allow for the analysis of the LCP's structure in space (Pieke and Krüger, 2007). In order to do this, vertices were added every 5m, which corresponds to the resolution of the DEM used, to the LCP using the densify tool in ArcGIS. The vertices were then converted to points, and the Generate Near Table tool was used to extract the distances from each point to the known Roman road, resulting in a CSV file that contained the distance values. Using the R package *ggplot2* (Wickham, 2009), the LCPs were plotted *(full code in Appendix C)*, with the thickness of the line corresponding to the distance from the predicted LCPs to the known Roman roads, resulting in a flow map.

3.8 Summary

Using the research gaps identified in Chapter Two, this chapter outlined the methods used to conduct the LCP analysis in the four study areas in the Highland and Lowland zone of Roman Britain. In particular, this chapter described how watercourses were incorporated within the LCP model, allowing for movement across bridges, as well as the inclusion of the Higuchi viewshed using distance multipliers. Furthermore, the LCP computation using the custom software *gdistance* was detailed, with the methodological assessment and validation of LCP results, which included the use flow maps, outlined.

CHAPTER FOUR: RESULTS

4.1 Introduction

The following chapter describes the accuracy of the LCPs, which were computed using the methods detailed in Chapter Three. The methodological assessment of the components within the LCP computation in the Gask Ridge study area will be assessed by using the validation methods outlined In Chapter Three, with the accuracy of the LCP results visually shown through the use of flow maps. Furthermore, the LCP results from the other three study areas will be addressed in the same way. Secondly, the accuracy of the LCPs which incorporate the Higuchi viewshed will be evaluated.

4.2 Methodological assessment

- **The Gask Ridge study area**

Figure 13 (overleaf) shows the computed LCPs for the Gask Ridge study area using 4, 8, and 16 directions with Tobler's Hiking Function.

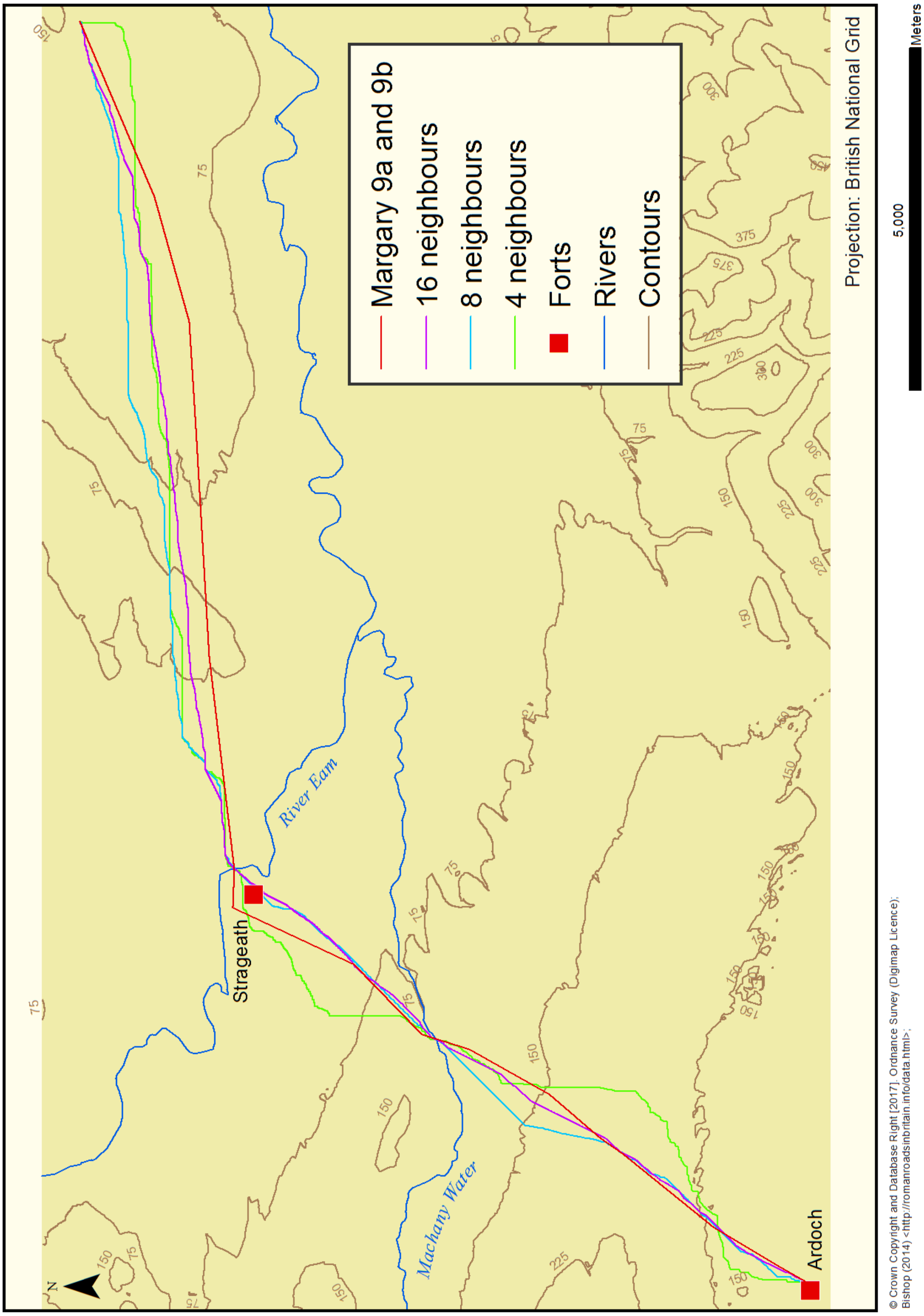


Figure 13: Computed LCPs for the Gask Ridge study area using 4, 8, and 16 directions

In agreement with the recommendation by Herzog (2014b), the use of more directions led to the most accurate prediction of the Margary 9a and 9b Roman road, with 64% of the LCP being within 250m of the known road (Table 1)

Number of directions	Within 250m (%)	Within 500m (%)	Within 1000m (%)
4	41	83	100
8	50	73	100
16	64	98	100

Table 1: Predicted LCP lying within distances from the known Margary 9a and 9b Roman road when using 4, 8, and 16 directions

Furthermore, the worst case distance decreased as the number of directions used in the LCP calculation increased (Figure 14), with the worst case distance decreasing to 347m when using 16 neighbours (Table 2, overleaf).

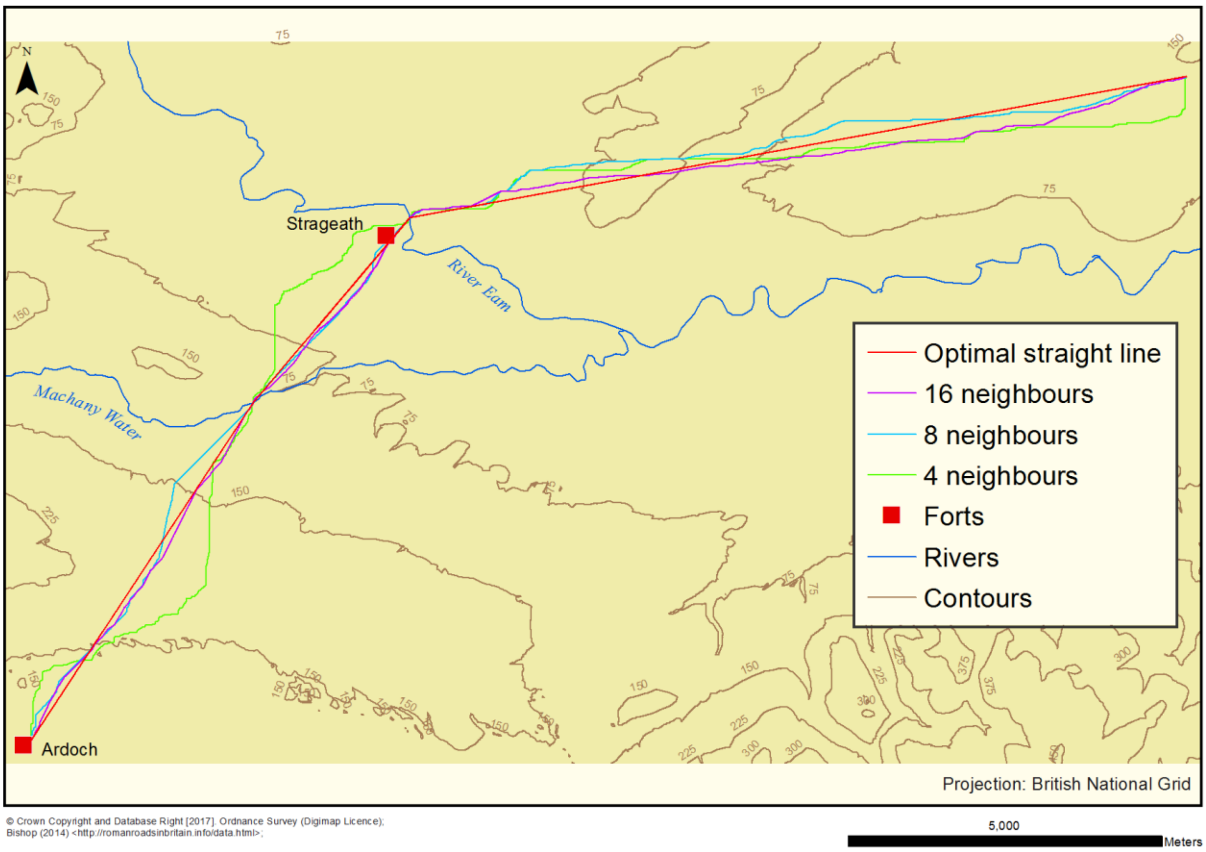


Figure 14: Computed LCPs for the Gask Ridge study area compared to the optimal straight line

Number of directions	Worst case distance (m)
4	867
8	381
16	347

Table 2: Distance from the optimal straight line to the LCP when using 4, 8, and 16 directions

The calculated LCP based on the OS Terrain 5 DTM (5m resolution) when using 16 directions and Tobler's Hiking Function is more accurate at predicting the Margary 9a and 9b Roman road compared to using the SRTM DEM (~23m resolution) (Figure 15), with 64% of the predicted LCP within 250m from the known Margary 9a and 9b Roman road (Table 3, overleaf). Furthermore, the average distance from the predicted LCP to the Margary 9a and 9b Roman is 166m when using OS Terrain 5, compared to 330m when using SRTM, whilst the maximum distance is 545m and 1154m, respectively.

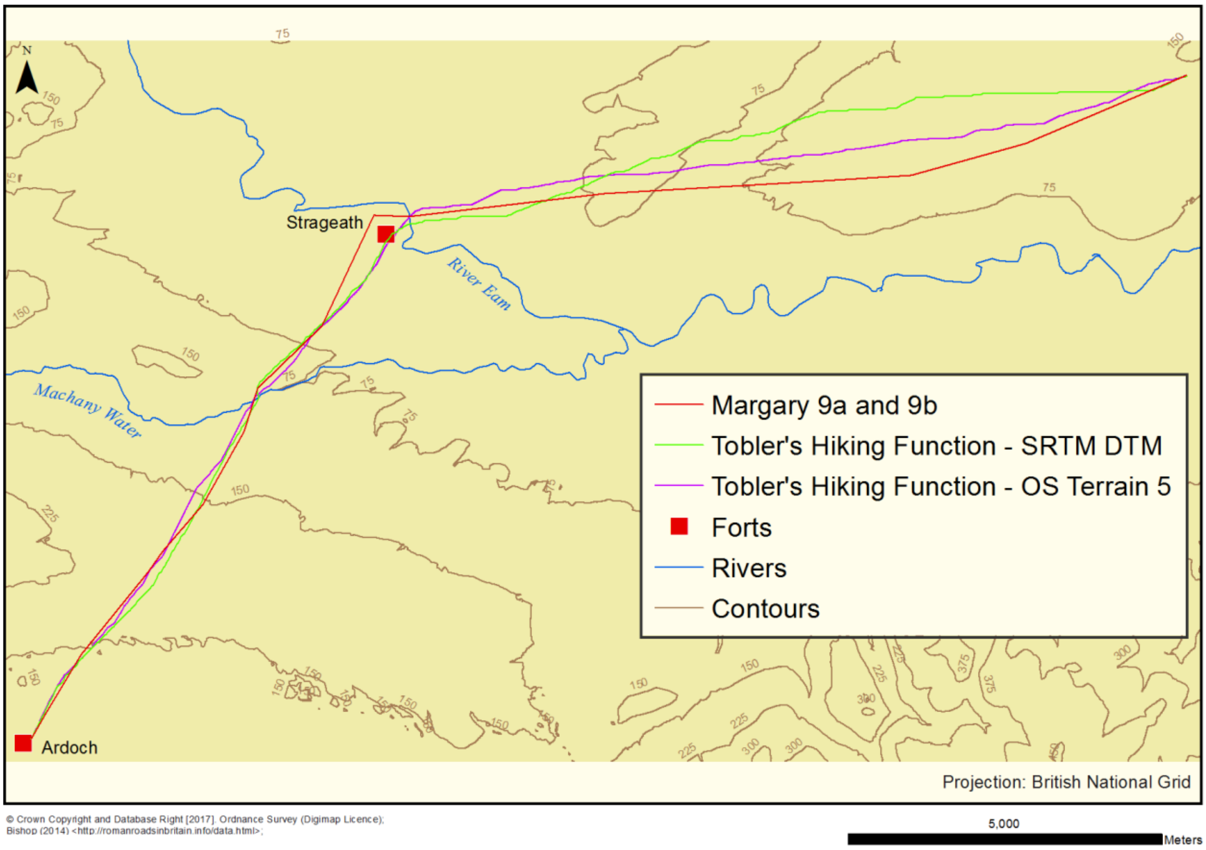


Figure 15: Computed LCP in the Gask Ridge study area using OS Terrain 5 and SRTM DEM

Cost function	Topography	Within 250m (%)	Within 500m (%)	Within 1000m (%)
Tobler’s Hiking Function	OS Terrain 5	64	98	100
	SRTM	60	71	89

Table 3: Predicted LCP lying within distances from the known Margary 9a and 9b Roman road when using different resolution topography

Using 16 directions and OS Terrain 5, which had been determined as producing the most accurate LCPs in the Gask Ridge study area, the three cost functions were compared to the Margary 9a and 9b Roman road (Figure 16, overleaf).

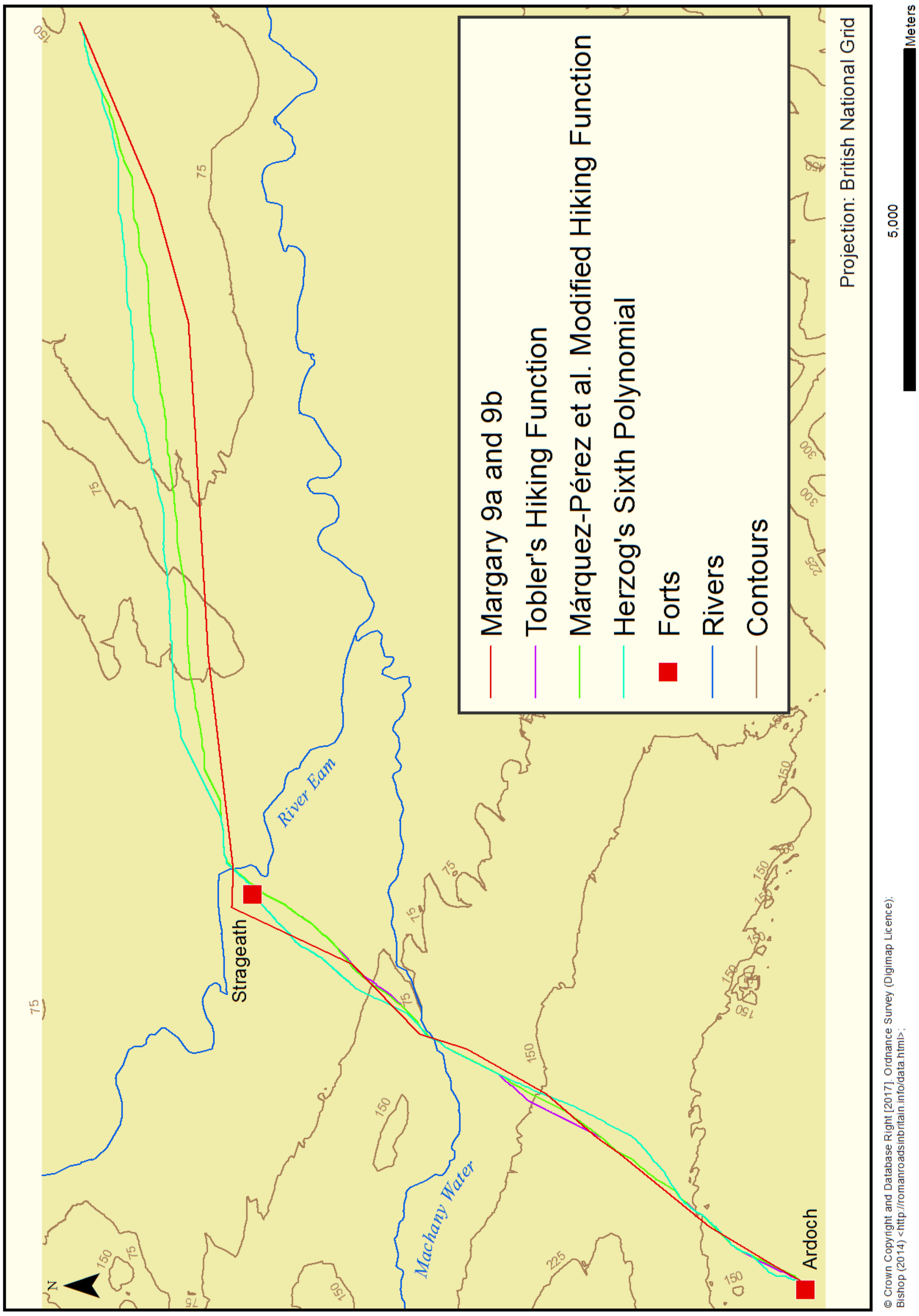


Figure 16: Computed LCPs in the Gask Ridge study area using different cost functions

Although not as visually obvious as the computed LCPs using the 4, 8 and 16 directions, it is noticeable that the energy based Herzog's Sixth Polynomial is the least accurate, whilst time based Tobler's Hiking Function and Márquez-Pérez et al. Modified Hiking Function produced similar LCPs, with 56% of the LCP lying within 250m from the known Margary 9a and 9b Roman road when using Herzog's Sixth Polynomial, compared to 64% when using both Tobler's Hiking Function and

Márquez-Pérez et al. Modified Hiking Function (Table 4). However, the average distance from the predicted LCP to the Margary 9a and 9b Roman road when using the Márquez-Pérez et al. Modified Hiking Function is 166m, compared to 172m when using Tobler's Hiking Function.

Cost Function	**Within 250m (%)**	**Within 500m (%)**	**Within 1000m (%)**
Tobler's Hiking Function	64	98	100
Herzog's Sixth Polynomial	56	67	100
Márquez-Pérez et al. Modified Hiking Function	64	98	100

Table 4: Predicted LCP lying within distances from the known Margary 9a and 9b Roman road when using different cost functions

Where the Márquez-Pérez et al. Modified Hiking Function deviated most significantly from the Margary 9a and 9b Roman road, with the distance between the computed LCP and the Roman road being greater than 250m, was between Parkneuk and Moss side, and south of Strageath (Figure 17, overleaf).

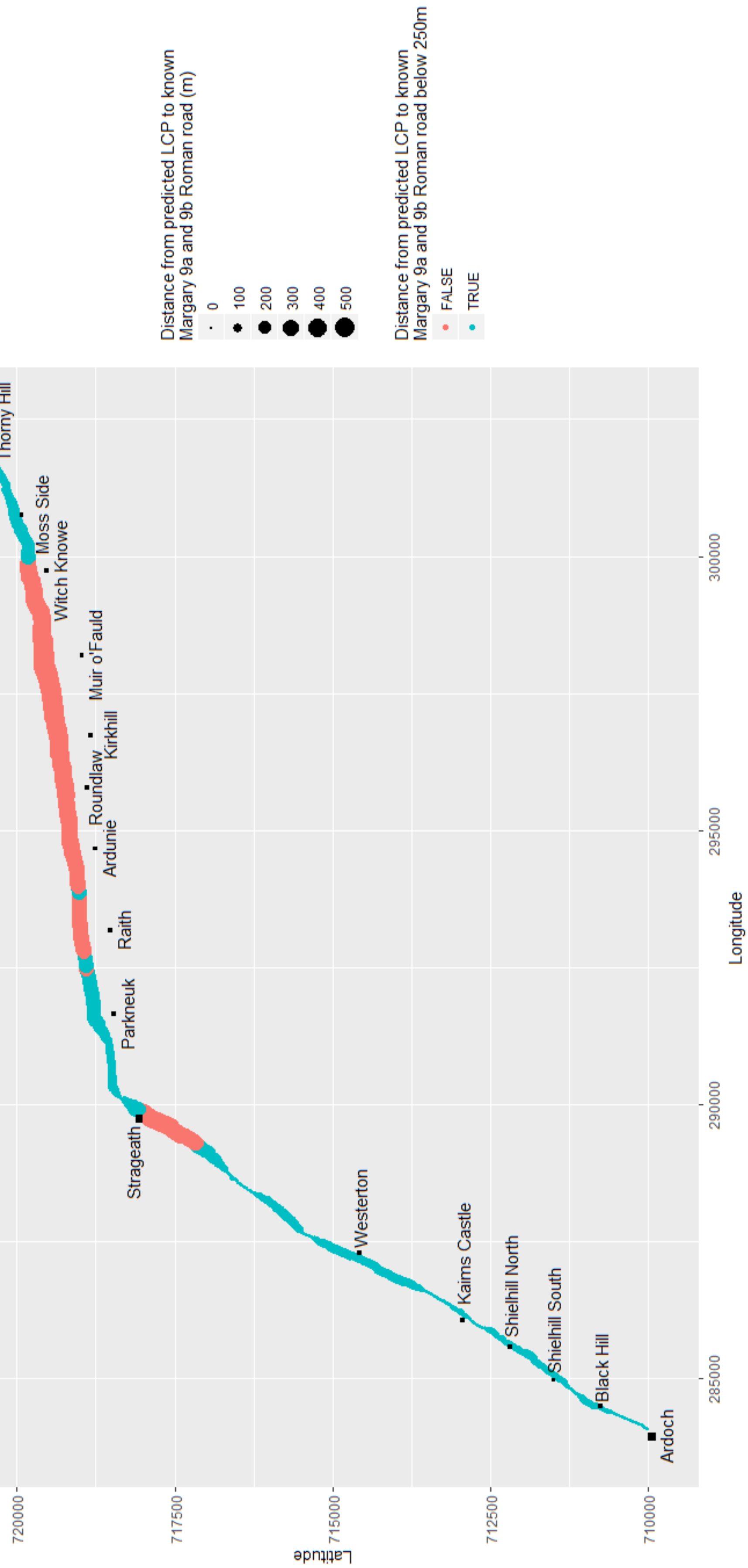


Figure 17: Flow map of the LCP in the Gask Ridge study area

In comparison to the predicted LCP the Gask Ridge study area based on the Modified Hiking Function, the LCP that incorporates the Higuchi viewshed (Figure 18) resulted in 77% being within 250m of the Margary 9a and 9b Roman road (Table 5, overleaf). Furthermore, the incorporation of the Higuchi viewshed reduced the average and maximum distance from the predicted LCP to the Margary 9a and 9b Roman road from 166m and 545m to 157m and 529m, respectively.

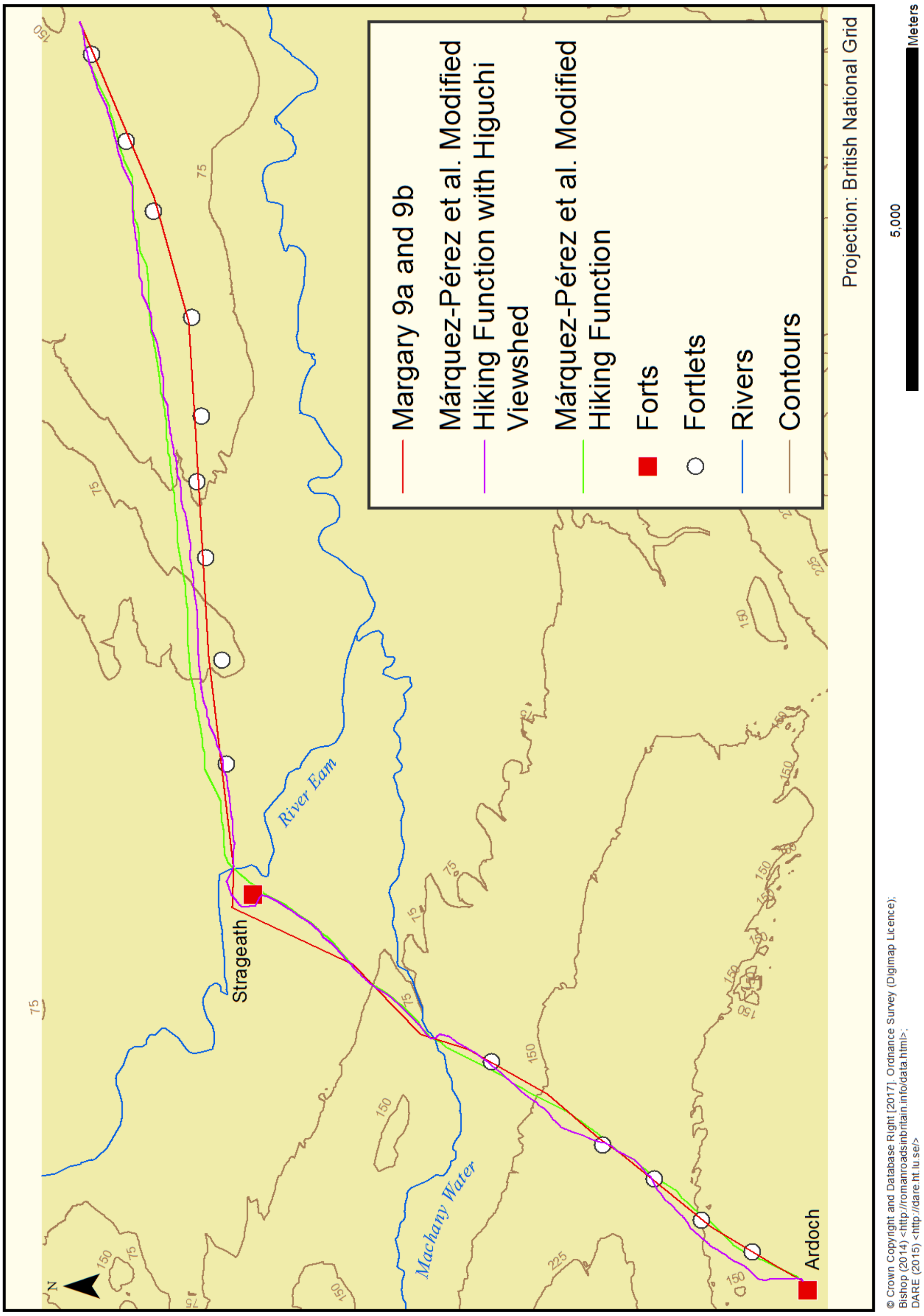


Figure 18: Computed LCPs in the Gask Ridge study area with Higuchi viewshed incorporated

	Within 250m (%)	**Within 500m (%)**	**Within 1000m (%)**
Márquez-Pérez et al. Modified Hiking Function	64	98	100
Higuchi Viewshed inclusion	77	98	100

Table 5: Predicted LCP lying within distances from the known Margary 9a and 9b Roman road when using 16 directions, Márquez-Pérez et al. Modified Hiking Function and the Higuchi viewshed

This increased accuracy of the predicted LCP when incorporating the Higuchi viewshed led to a greater predictive accuracy of the Margary 9a and 9b Roman road between Parkneuk and Moss Side, with the section of the LCP predicted greater than 250m from the Margary 9a and 9b Roman road decreasing from Parkneuk to Moss side, to Roundlaw fortlet to Moss side (Figure 19, overleaf)

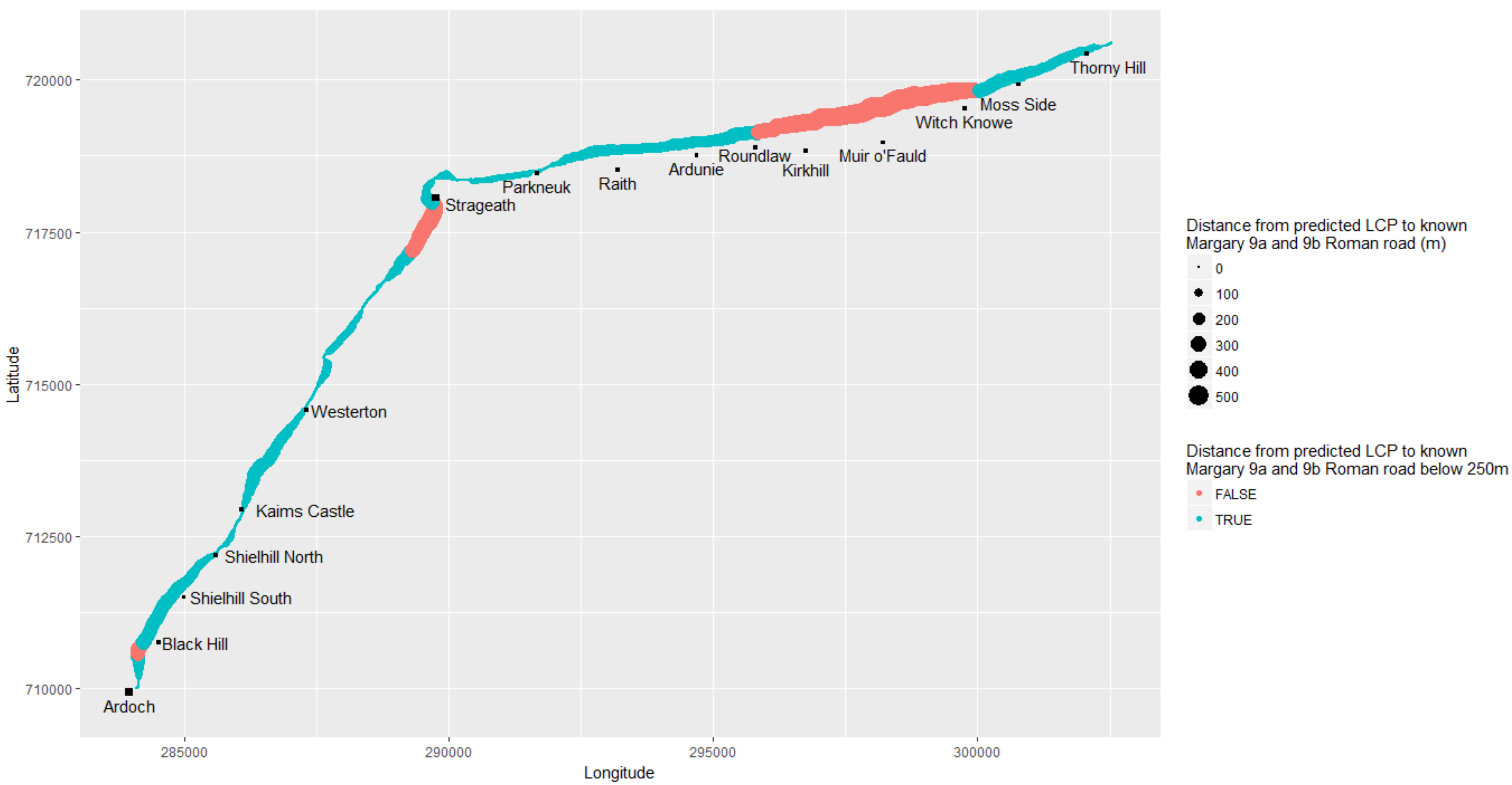


Figure 19: Flow map of the LCP in the Gask Ridge study area when Higuchi viewshed incorporated

4.2 The Stanegate study area

Using the same components that were identified as computing the most accurate LCP in the Gask Ridge study area, the LCP in the Stanegate study area was calculated (Figure 20, overleaf).

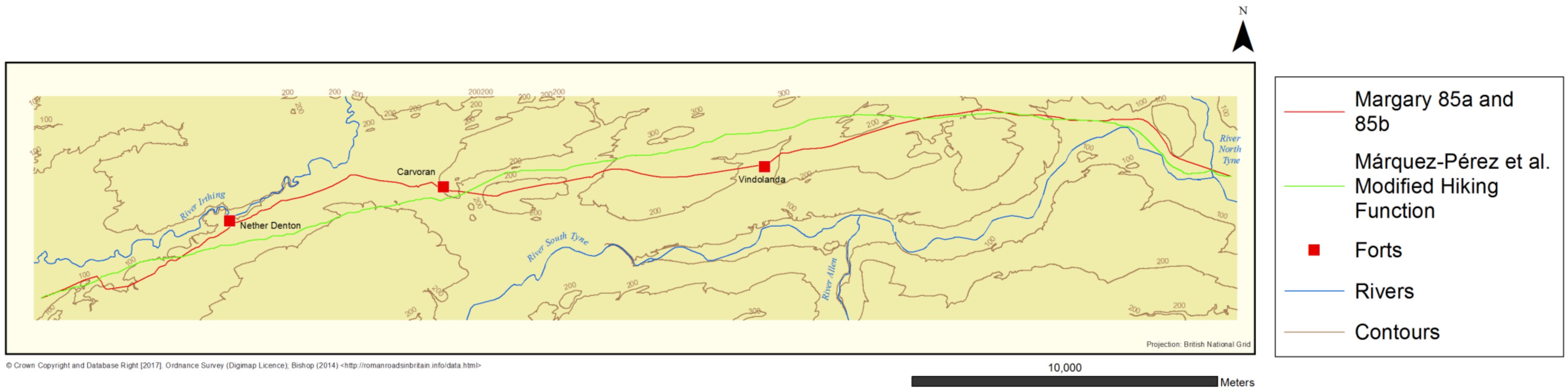


Figure 20: Computed LCP in the Stanegate study area

Although not as accurate as the predicted LCP in the Gask Ridge study area, more than a third of the LCP in the Stanegate study area is within 250m from the Margary 85a and 85b Roman road (Table 6). Furthermore, the average and maximum distance from the predicted LCP to the Margary 85a and 85b Roman road is 443m and 1142m.

	Within 250m (%)	**Within 500m (%)**	**Within 1000m (%)**
Stanegate study area	36	61	93

Table 6: Predicted LCP lying within distances from the known Margary 85a and 85b Roman road when using 16 directions and the Márquez-Pérez et al. Modified Hiking Function

Where the computed LCP best predicts the Margary 85a and 85b Roman road, with a distance from the LCP to the Roman road being below 250m, is on either side of the Newbrough fortlet and near Carvoran (Figure 21, overleaf).

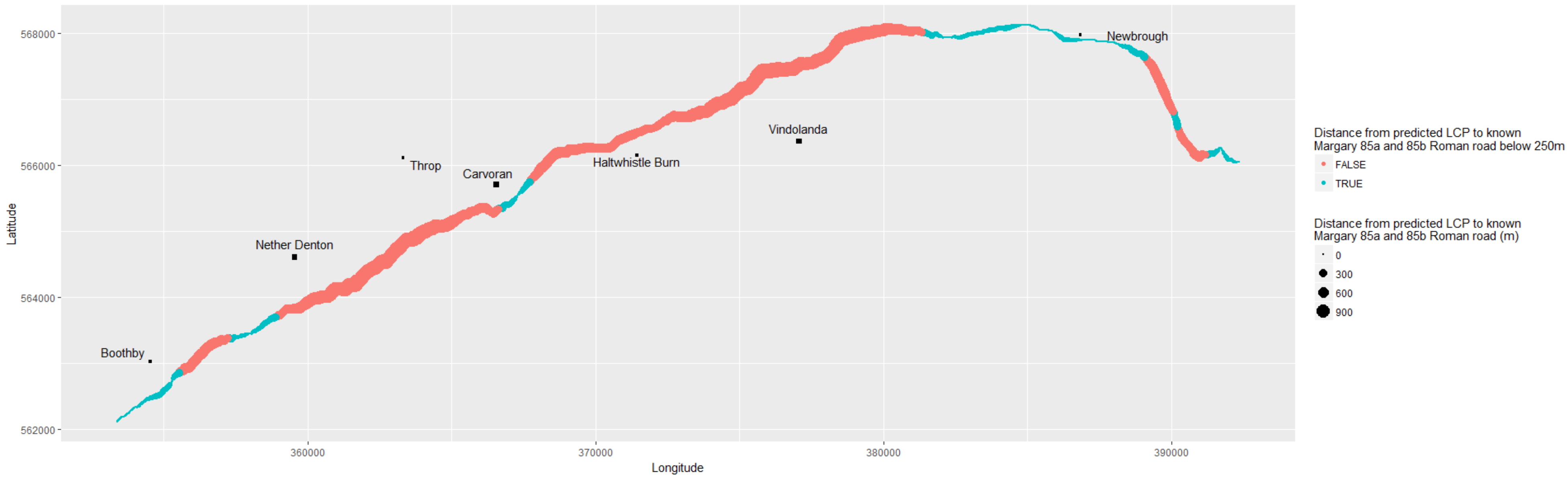


Figure 21: Flow map of the LCP in the Stanegate study area

The predicted LCP that incorporates the Higuchi viewshed resulted in a computed LCP that showed greater departure from the Margary 85a and 85b when compared to the LCP that does not incorporate the Higuchi viewshed (Figure 22, overleaf). This trend becomes more evident when comparing the LCP within 500m of the known Roman road, with 61% predicted when not incorporating the Higuchi viewshed and 57% when incorporating the Higuchi viewshed (Table 7, page 58). Similarly, the average and maximum distance from the predicted LCP to the Margary 85a and 85b Roman road increased from 443m and 1142m to 517m to 1506m.

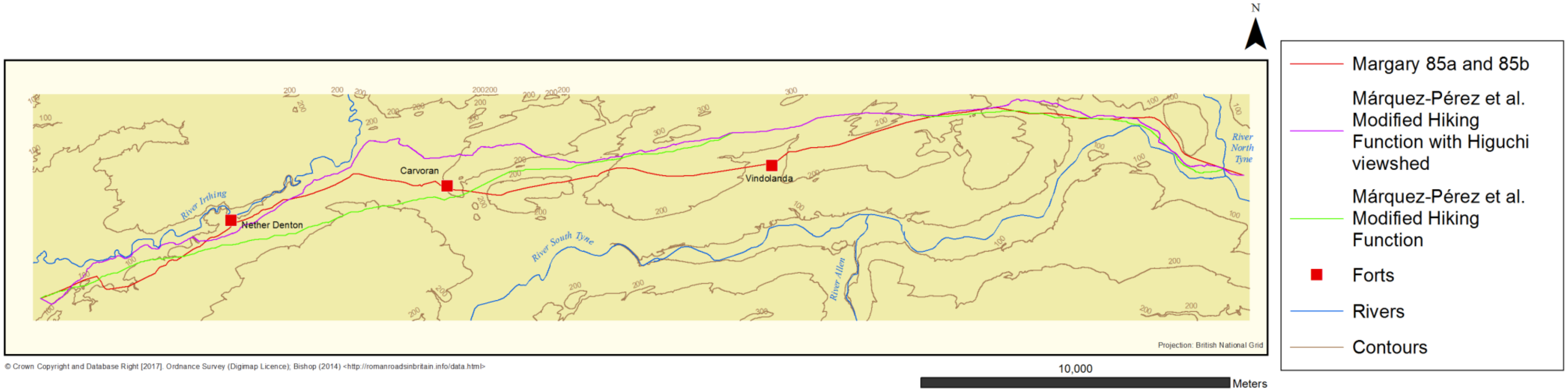


Figure 22: Computed LCPs in the Stanegate study area with Higuchi viewshed incorporated

	Within 250m (%)	**Within 500m (%)**	**Within 1000m (%)**
Stanegate study area	36	61	93
Higuchi Viewshed inclusion	35	57	82

Table 7: Predicted LCP lying within distances from the known Margary 85a and 85b Roman road when using 16 directions, Márquez-Pérez et al. Modified Hiking Function and Higuchi viewshed

In addition, the computed LCP predicts the known Roman road near Newbrough less accurately than when not including the Higuchi viewshed. However, the computed LCP does predict more accurately around Nether Denton (Figure 23, overleaf).

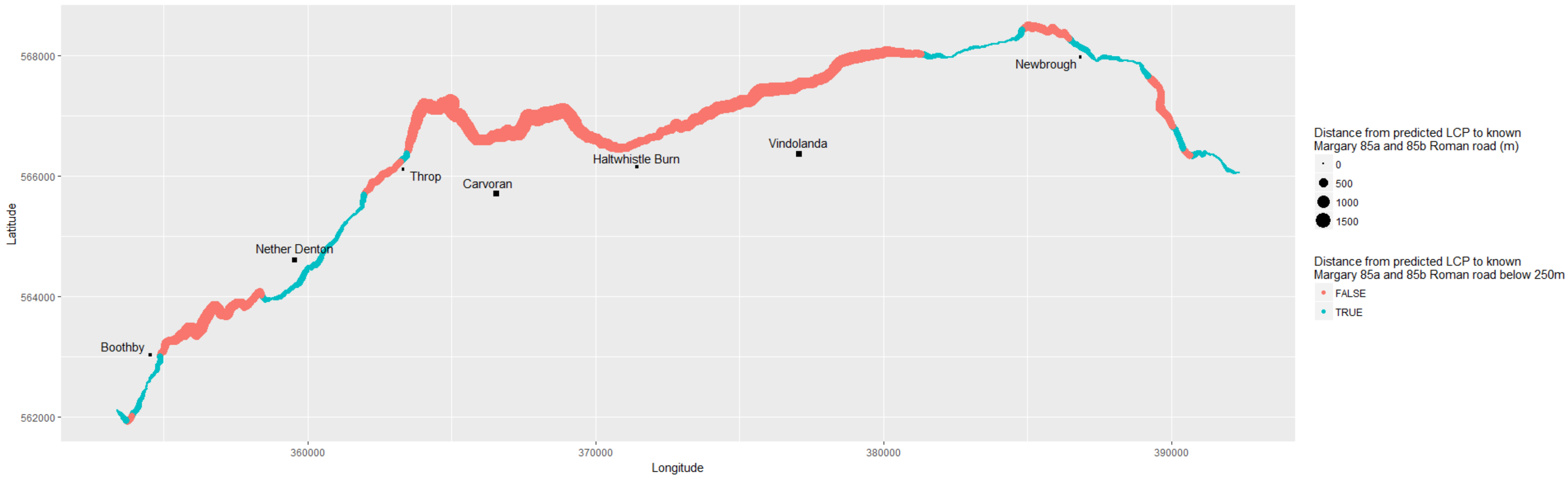
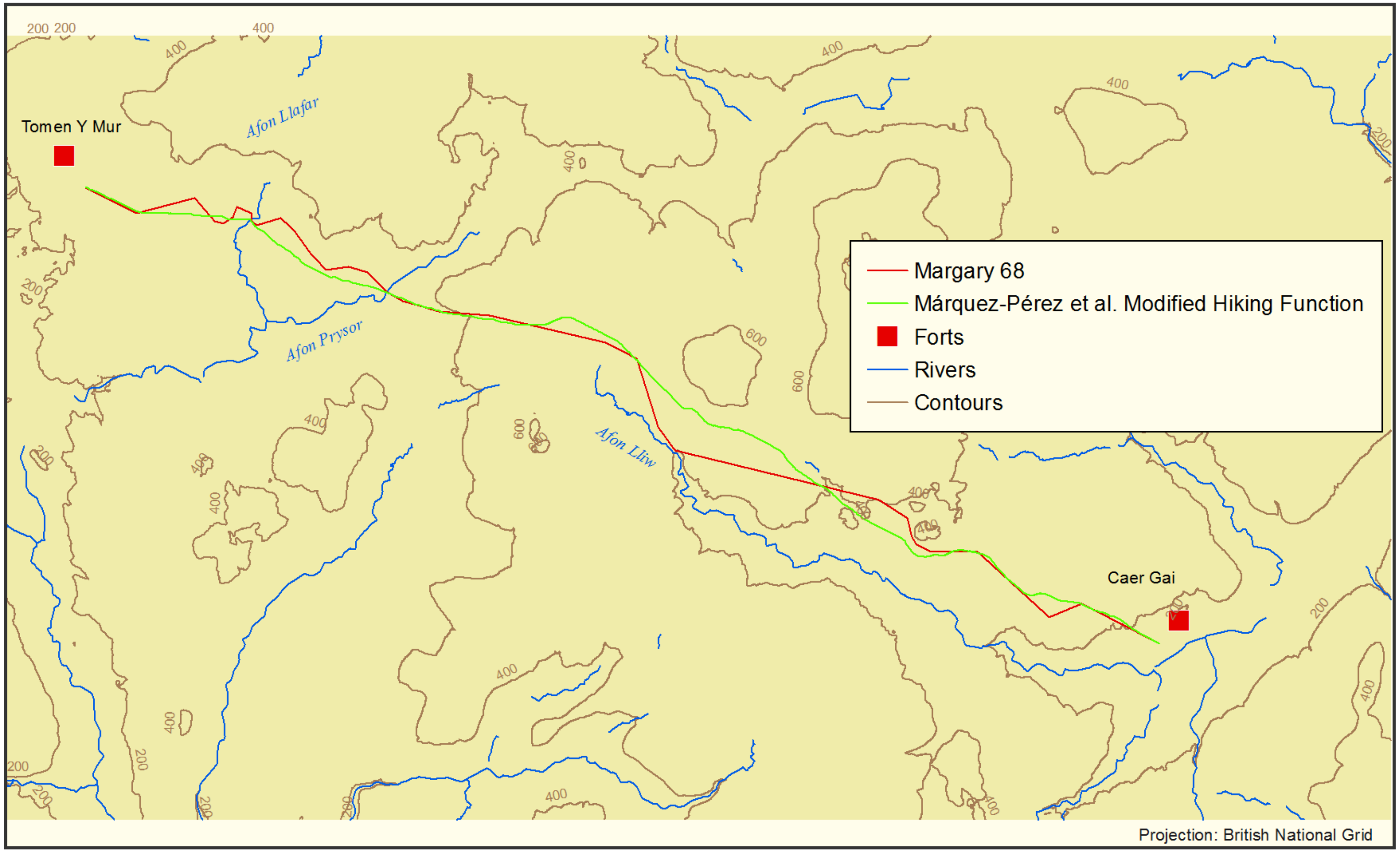


Figure 23: Flow map of the LCP in the Stanegate study area when Higuchi viewshed incorporated

4.3 Tomen Y Mur – Caer Gai study area

The LCP computed in the Tomen Y Mur – Caer Gai study area follows the Margary 68 Roman road closely (Figure 24, overleaf), with 83% within 250m, and further increasing to 96% within 500m (Table 8, page 63). Furthermore, the average distance from the predicted LCP to the Margary 68 Roman road is 127m, with the maximum distance being 605m.



Bishop (2014) <http://romanroadsinbritain.info/data.html>

Figure 24: Computed LCP in the Tomen Y Mur – Caer Gai study area

	Within 250m (%)	**Within 500m (%)**	**Within 1000m (%)**
Tomen Y Mur – Caer Gai study area	83	96	100

Table 8: Predicted LCP lying within distances from the known Margary 68 Roman road when using 16 directions and the Márquez-Pérez et al. Modified Hiking Function

Where the predicted LCP most deviates from the Margary 68 Roman road, with the distance from the LCP to the Roman road being greater than 250m (Figure 25, overleaf), is where the Roman road moves southwards, to run parallel with the River Lliw (Figure 26, page 64).

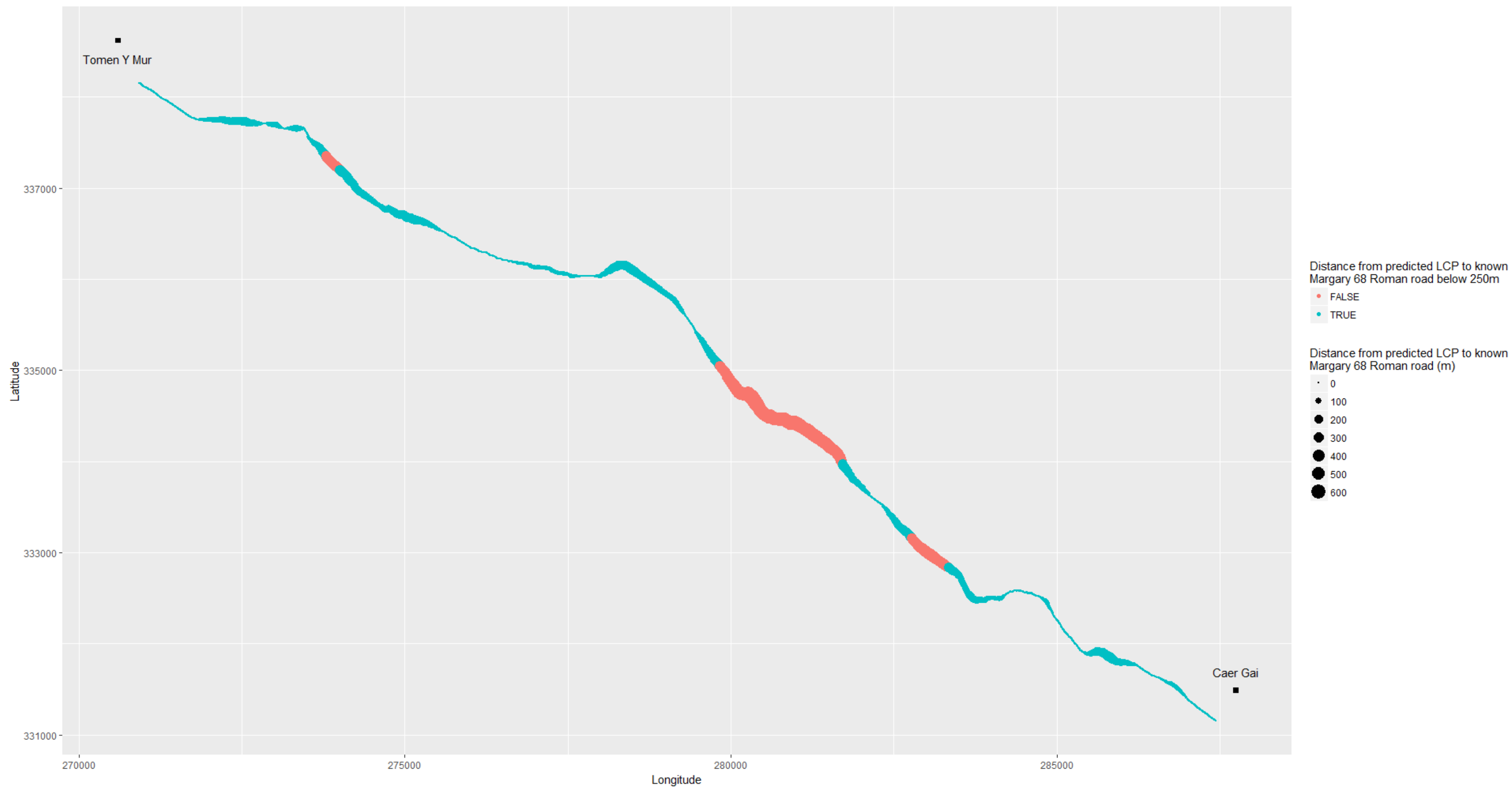


Figure 25: Flow map of the LCP in the Tomen Y Mur – Caer Gai study area

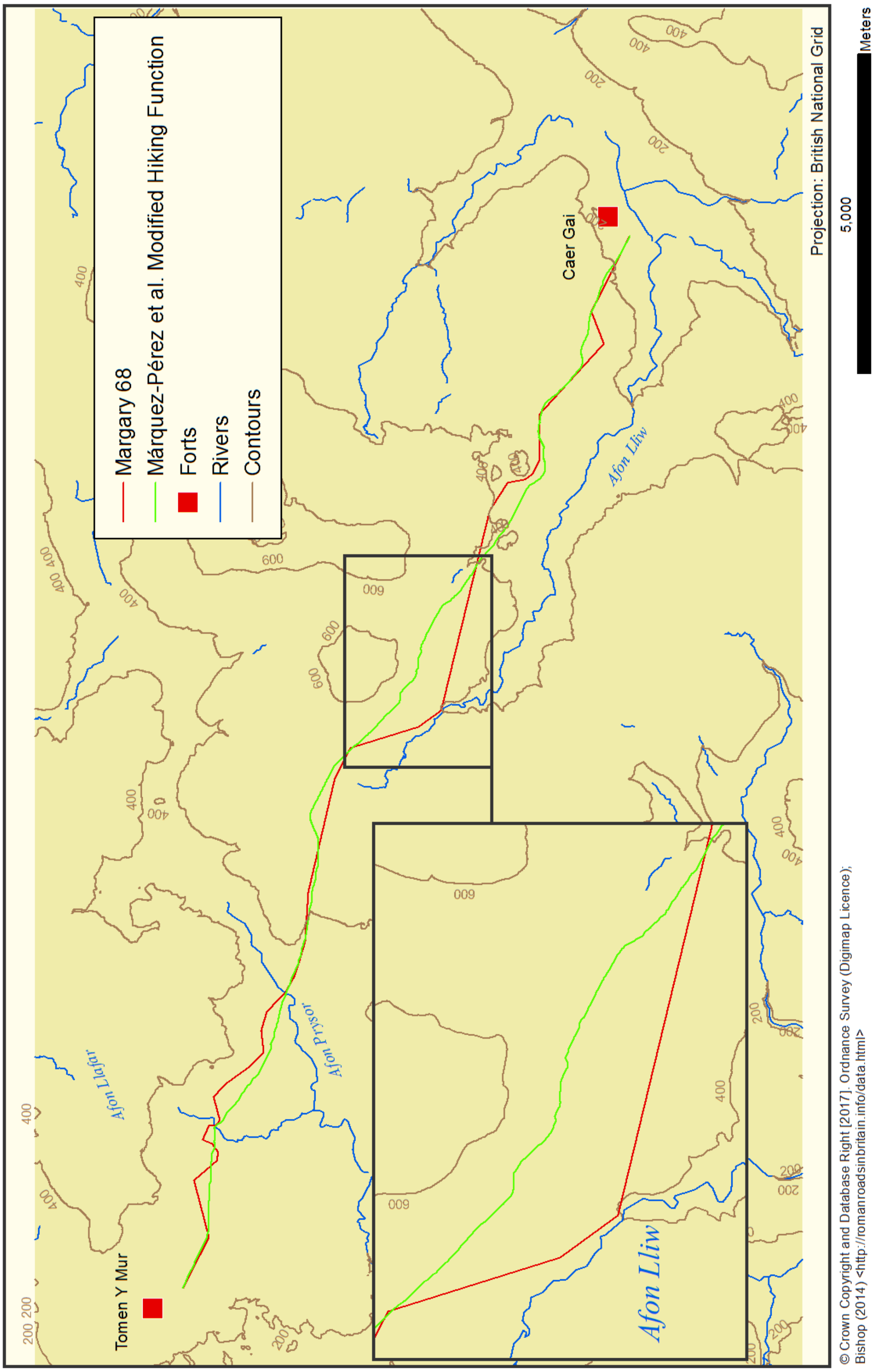


Figure 26: Roman road in Tomen Y Mur – Caer Gai study area showing deviation to river Lliw

4.4 Benenden - Canterbury study area

Figure 27 shows the computed LCP from Benenden to Canterbury, with 31% lying within 250m from the Margary 130 Roman road (Table 9, overleaf). Furthermore, the average and maximum distance from the predicted LCP to the Margary 130 Roman road is 1015m and 2617m.

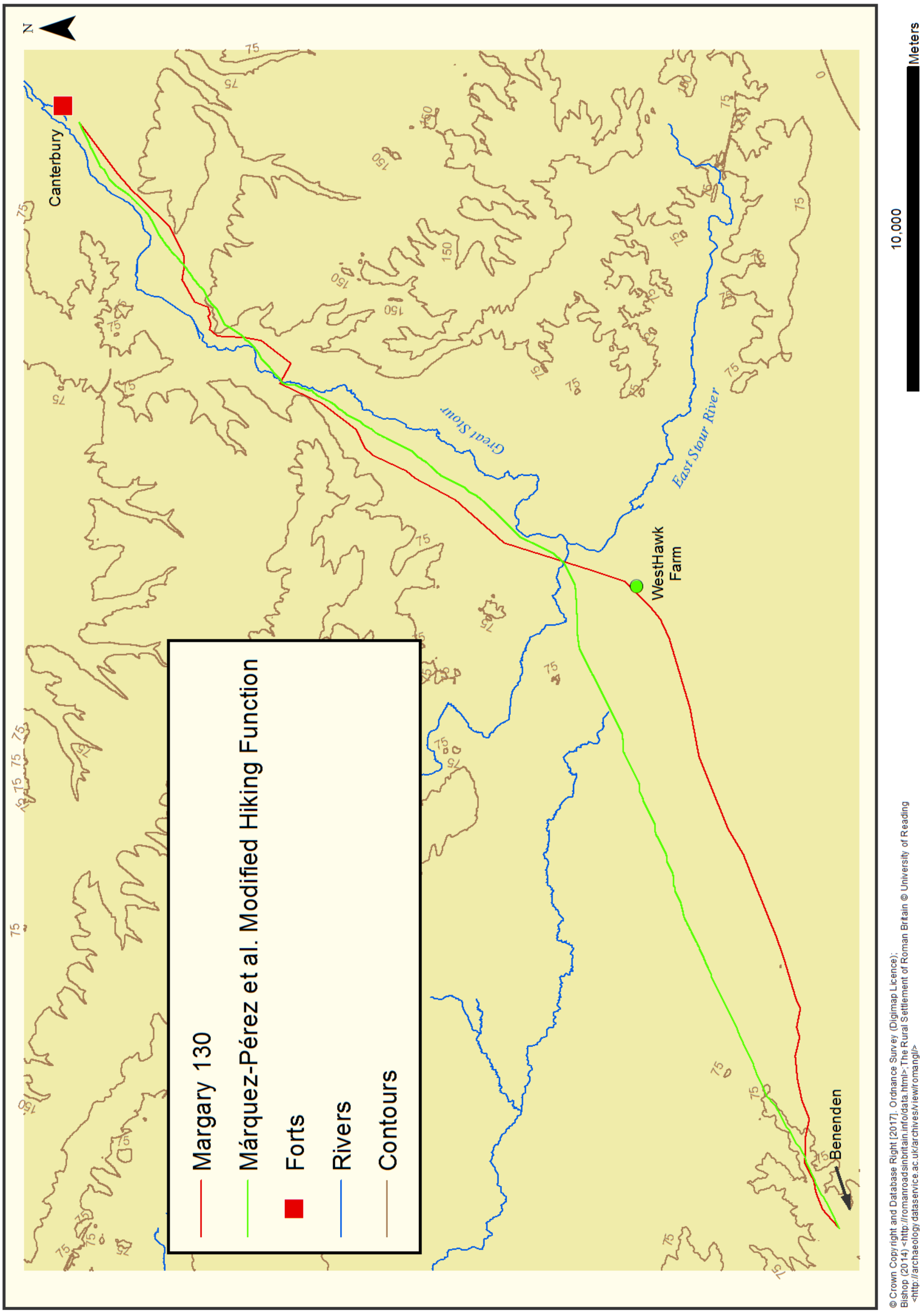


Figure 27: Computed LCP in the Benenden - Canterbury study area

	Within 250m (%)	**Within 500m (%)**	**Within 1000m (%)**
Benenden - Canterbury study area	31	50	62

Table 9: Predicted LCP lying within distances from the known Margary 130 Roman road when using 16 directions and the Márquez-Pérez et al. Modified Hiking Function

Where the computed LCP predicts the Roman road least accurately is between Benenden and the Great Stour Crossing (Figure 28, overleaf), with the distance from the predicted LCP to the Roman road being greater than 250m.

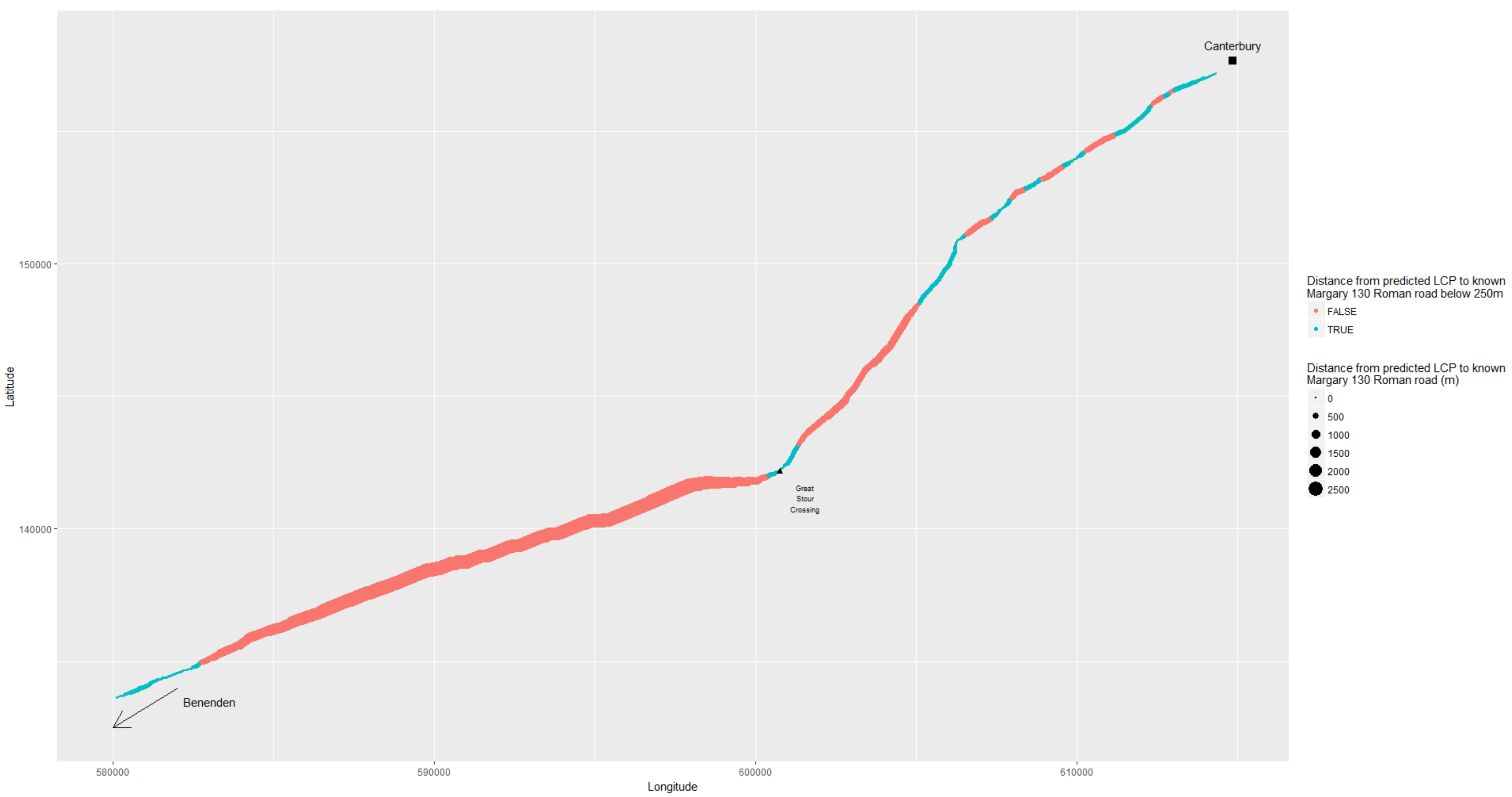


Figure 28: Flow map of the LCP in the Benenden - Canterbury study area

4.5 Summary

By performing a methodological assessment of the components within the LCP computation, the computed LCPs show that the highest number of directions, the highest resolution DEM, and the Márquez-Pérez et al. (2017) Modified Hiking Function, produced the most accurate LCPs.

Lastly, the results from the four study areas show that the accuracy of the LCPs are divided into two groups, with the division coinciding with the study areas in the Highland (The Gask Ridge; The Stanegate; and Tomen Y Mur – Caer Gai) and the Lowland zone (Benenden – Canterbury) of Roman Britain (Figure 29).

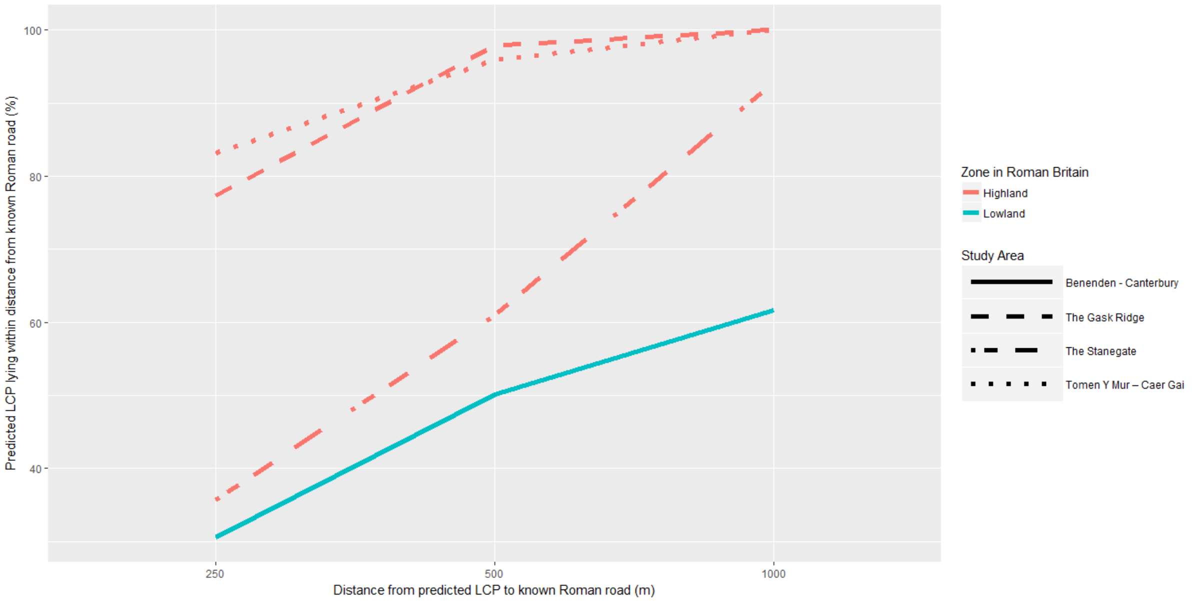


Figure 29: Accuracy of the computed LCPs in the four study areas

This division in accuracy is also seen when comparing the worst case distance from the predicted LCPs to the Roman roads (Figure 30, overleaf).

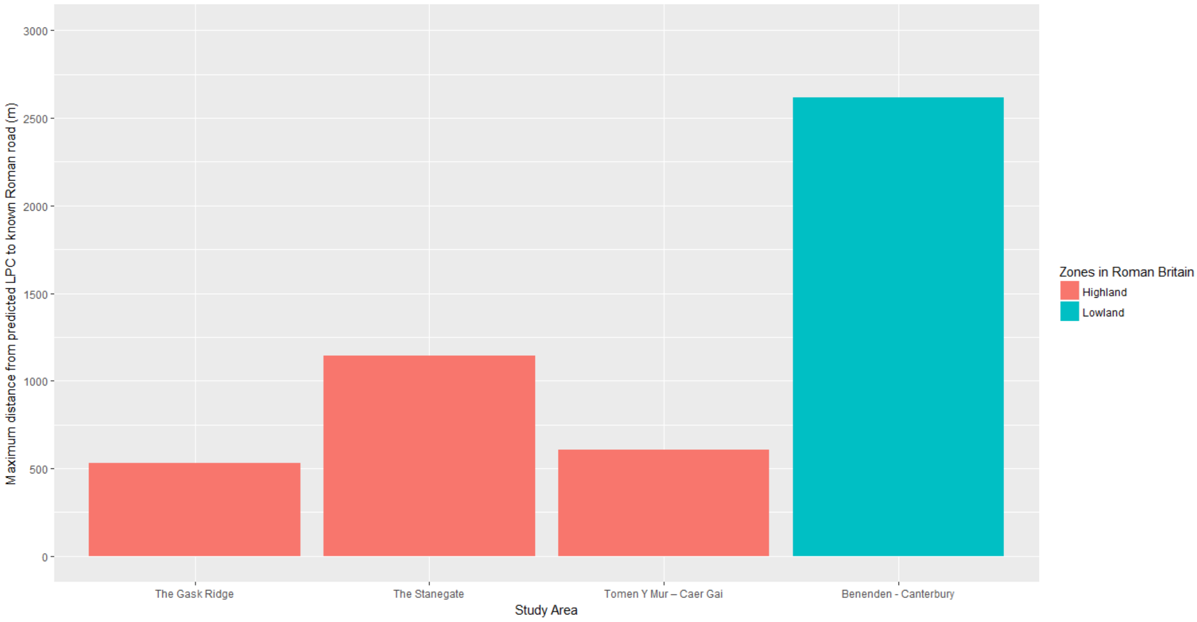


Figure 30: Worst case distance from the computed LCPs to the Roman roads in the four study areas

CHAPTER FIVE: DISCUSSION

5.1 Introduction

To examine the LCP analysis results, Chapter Five is divided into three parts. Firstly, the methodological assessment of the LCP components will be investigated, with the technical success of the LCP computations discussed. Furthermore, limitations and potential improvements to the LCP computation will be addressed. Secondly, the increased accuracy of the LCPs computed in the Highland zone will be discussed, linking the results to previous archaeological and LCP analysis research. Furthermore, the methods used to validate the computed LCPs will be discussed, with a focus on the success of the use of the proposed flow maps. Lastly, the use of Higuchi viewshed on the accuracy of the LCPs will be discussed.

5.2 Methodological assessment

Through comparing the computed LCPs when using 4, 8 and 16 directions in the Gask Ridge study area, it was found that the accuracy of the predicted LCPs increased when increasing the number of directions of movement in the LPC calculation. These results agree with that stated by Herzog (2013b) and Wheatley and Gillings (2002), who noted that the increased accuracy of the LCP is due to the increased number of options for the LCP to move, thus increasing the ability for the LCP to take the most efficient route. This is evident through the accumulated cost surface of constant cost resembling more of a circle as the number of directions available for travel increases (Figure 31), as well as a reduction in the cost of travel from 6084 to 4862, when using 4 and 16 directions, respectively.

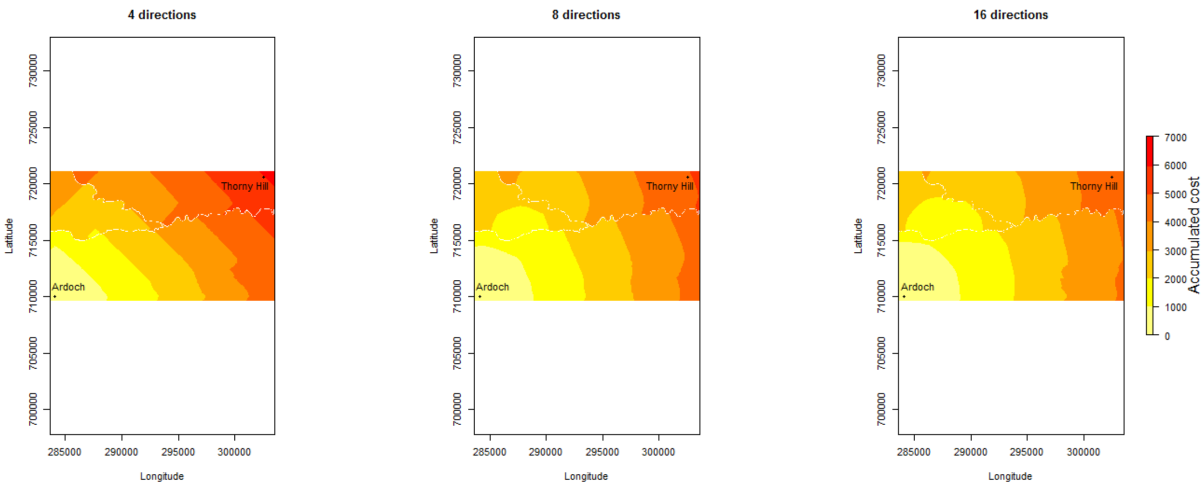


Figure 31: Accumulated cost surface for the Gask Ridge study area when using 4, 8, and 16 directions

Therefore, these results suggest that, in agreement with Herzog (2014b), the use of 4 and 8 directions, such as that used in ArcGIS, produce incorrect accumulated cost surfaces, and are therefore insufficient to accurately predict the location of Roman roads. However, the use of 16 directions in this study is below that suggested by Harris (2002) who recommended 48 directions, and Huber and Church (1985) who recommended 24 directions. Therefore, it is possible that a greater number of directions would have resulted in a more accurate LCP, with the algorithm incorporating increased knowledge of the landscape (Lock and Pouncett, 2010). Nonetheless, this thesis has shown that a minimum of 16 directions should be used in future LCP studies. Similarly, custom software should be developed that allows for both 24 and 48 directions, with future studies assessing the LCPs produced when using these greater directions.

In addition, the use of the OS Terrain 5 was found to be more accurate at predicting the location of the known Margary 9a and 9b Roman road compared to the SRTM. This is likely due to the lower resolution SRTM "flattening the slopes" (Vieux, 2016, p.76), which can lead to slopes and ridges of a landscape being poorly represented in the elevation model (Becker et al., 2017; Herzog, 2012; Wheatley and Gillings, 2002), resulting in an incorrect terrain cost surface, and therefore producing an inaccurate LCP. For instance, the steepest positive mathematical slope derived from the OS Terrain 5 DTM is 0.78, compared to 0.28 from the SRTM. Moreover, only 0.2% of the Gask Ridge study area has positive mathematical slope as steep or steeper than 0.10 when using the SRTM, compared to 21% of the study area when based on the OS Terrain 5 (Figure 32).

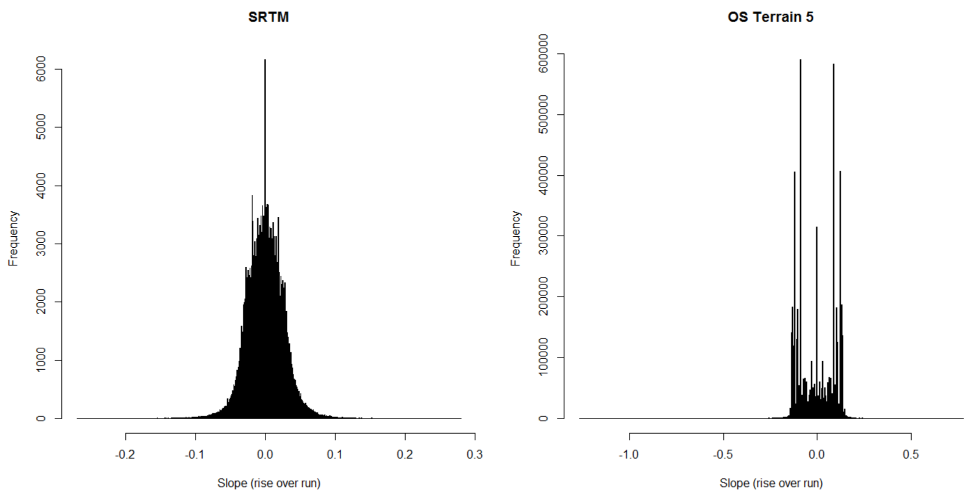


Figure 32: Slope distribution of the SRTM and OS Terrain for the Gask Ridge study area

The increased accuracy of the predicted LCP when using the higher resolution OS Terrain 5 disagrees with Herzog and Posluschny (2011), who noted that some archaeologists believe that a low resolution DEM comes closer to the human perception of a landscape. Instead, these findings reinforce that already stated by Becker et al. (2017); Conolly and Lake (2006); and Wheatley and Gillings (2002), further suggesting that higher resolution DEMs, which represent the topography more accurately, are used in future LCP analysis.

From the comparison of the LCPs when using different cost functions, it was found that the time based Márquez-Pérez et al. Modified Hiking Function produced the most accurate reconstruction of the Roman road in the Gask Ridge study area. This challenges what was recommended by Herzog and Posluschny (2011), who preferred to use cost functions based on energy rather than time expenditure, and instead agrees with Livingood (2012) who recommended the use of time based cost functions, as historical accounts were recorded in time rather than energy expenditure, and further suggests that time based cost functions should be used when predicting ancient roads. However, as stated by Mlekuž (2014), computed LCPs are extremely sensitive to the algorithms used, with Rademaker et al. (2012) believing that more reliable results are obtained by experimenting with cost values. Nonetheless, this thesis has shown that the time based Márquez-Pérez et al. Modified Hiking Function generates a more accurate LCP in the Gask Ridge study area than the more popular and widely used time based Tobler’s Hiking Function, suggesting that the Modified Hiking Function, with the increased precision due to the MIDE component, may offer an alternative to Tobler’s Hiking Function.

5.3 Comparison of the LCPs in the Highland and Lowland Zone of Roman Britain

The computed LCPs in the three study areas in the Highland zone of Roman Britain, which include the Gask Ridge; the Stanegate; and Tomen Y Mur – Caer Gai, showed greater predictive accuracy than the computed LCP in the Benenden – Canterbury study area in the Lowland zone of Roman Britain. These results agree with the hypothesis proposed that the LCP analysis of Roman roads in Roman Britain would predict the location of the known Roman roads in the Highland zone of Roman Britain more accurately than in the Lowland zone of Roman Britain due to social factors having a greater influence on the construction of Roman roads in the Lowland zone of Roman Britain. Furthermore, this agrees with Murrieta-Flores (2010) who stated that LCP analysis is unable to model influences such as social phenomena adequately, and further strengthens the assessment that LCP analysis is “environmentally deterministic” (Herzog, 2013b, p.187), due to the predicted LCPs being more accurate in areas where the topography had a greater influence in determining where the Roman roads were constructed.

However, there are some variances in the accuracy of the predicted LCPs between study areas in the Highland zone. For instance, the predicted LCP within 250m from the known Roman road in the Stanegate study area is 36%, compared to 64% and 83% for the Gask Ridge and Tomen Y Mur – Caer Gai study areas, respectively. The decrease in the accuracy of the predicted LCP in the Stanegate suggests that environmental factors did not dictate the construction of the Roman road. This is further strengthened by Poulter (2010, p.50), who stated that the Stanegate Roman road is "riddled with unnecessary curving lines, steep inclines and declines, and awkward stream and river crossings", leading him to suggest that the Roman road was built after the location of the forts and fortlets were decided. Similarly, the area where the LCP most inaccurately predicts the Roman road in the Tomen Y Mur – Caer Gai study area is where the Roman road moves to run parallel with the river. This departure is likely to enable water transportation (Jones, 2004; Jones and Mattingly, 1990), thus being influenced by social factors rather than topographical, which is reflected in the decrease of accuracy of the LCP in predicting the location of the known Roman road in this area. Therefore, even though the LCPs computed in the Highland zone were more accurate than the Lowland zone, the areas where the LCPs predict less accurately can be attributed to the environmental determinism of LCP analysis, and its inability to adequately model social factors that may have dictated the construction of the roads. Furthermore, these results strengthen that reflected by Güimil-Fariña and Parcero-Oubiña (2015, p.33), who stated that formalised network of roads, which imposed a strong discipline over the landscape, are “very well suited” to LCP analysis, rather than “fluid, unstable, and easily changing forms of mobility”.

The use of the method proposed by Goodchild and Hunter (1997) has been successful at reporting the accuracy of the LCPs, as well as allowing for comparison between computed LCPs. Furthermore, the worst case distance method has been effective in showing the accuracy of the LCP. However, this thesis has shown that the use of flow maps allow for greater exploration of the LCP results, as well as greater clarity when comparing LCPs computed using different components. Furthermore, flow maps have allowed for more precise identification of where the accuracy of the LCPs differs, and should therefore be used in future LCP analysis studies.

Nonetheless, there are limitations which could have affected the ability of the LCP analysis to predict the location of the Roman roads. For instance, locations are given meaning in relation to physical surroundings and cultural experiences (Hu, 2012; Wheatley and Gillings, 2002), which even the most simplistic archaeological models have to make assumptions about (Kuhn et al., 2004). Furthermore, these assumptions are continually reconstructed by archaeologists, and therefore “fluid, relative, and subjective”, and might not reflect past cognitive processes that dictated decisions made by people in the past (Verhagen and Whitley, 2012, p.60). However, this study has shown that LCP analysis is a viable technique for recreating aspects of the cognitive landscape of Roman people in the Highland zone, where the terrain posed constraints on the location of the roads.

5.4 Inclusion of the Higuchi viewshed

By incorporating the Higuchi viewshed in the LCP calculation for the Gask ridge and Stanegate study area, the accuracy of the predicted LCP both increased and decreased, respectively. The increase in accuracy of the predicted LCP in the Gask ridge study area when including the Higuchi viewshed reflects that found in Hanson and Maxwell (1986) and Breeze (1982), who stated that the location of the road was dictated by the need for the fortlets to see what was happening, and to control movement along it. Conversely, the decrease in the accuracy of the predicted LCP in the Stanegate study area when including the Higuchi viewshed suggests that visibility was not a key factor in the location of the Roman road, and counters that thought by Hanson and Maxwell (1986), who stated that surveillance and control of movement through the area was important. Due to this, the incorporation of the Higuchi viewshed within LCP analysis has been shown to be effective at determining whether the cultural factor of visibility dictated the location of Roman roads, and strengthens that thought by Lake and Woodman (2003), who noted that Higuchi viewshed can lead to environmental deterministic deductions about human behaviour. Furthermore, the Higuchi viewshed offers a clearer and more objective framework in comparison to previously used viewshed methods, and overcomes the limitations regarding the assumption of 20:20 vision (Wheatley and Gillings, 2000). In addition, the Higuchi viewshed using the distance multipliers as calculated by Ogburn (2006) has been shown to offer a practical quantitative method to assess the level of clarity of objects over distance, as well as being able to identify areas where the Roman roads were located as to ensure the clarity of visibility was perfect. However, according to Jacobson (2007), the distance multipliers used in the Higuchi viewshed may overestimate the degree of visibility within a landscape, as well not taking into account the reflective nature of the object. Nonetheless, the Higuchi viewshed has been shown to increase the accuracy of LCPs in areas where the Roman roads were dictated by the need to be visible.

5.5 Summary

Through the methodological assessment, the accuracy of the computed LCPs has been shown to be sensitive to the components included. However, this thesis has determined that the accuracy of the LCP increases when using more directions, higher resolution DEMs, and the time based Márquez-Pérez et al. (2017) Modified Hiking Function. Furthermore, the greater accuracy of the LCPs in the Highland zone further strengthens the thought that LCP analysis is environmentally deterministic, and suggests that the use of LCP analysis is more suitable to areas where the terrain impose constraints on the location of Roman roads. In addition, flow maps have been shown to allow for greater exploration of the LCP results over previously used validation methods. Lastly, the use of the Higuchi viewshed has been shown to be an effective method at determining whether visibility was important.

CHAPTER SIX: CONCLUSION

In conclusion, this thesis assessed the suitability of LCP analysis for the prediction of the location of known Roman roads in Roman Britain. As hypothesised, the LCPs generated for study areas in the Highland zone of Roman Britain were more accurate at predicting the location of known Roman roads than the LCPs computed in the Lowland zone.

Furthermore, three main points have been concluded from this study, each offering recommendations for future LCP analyses. Firstly, this study suggests that, unless the social features of the study area in Roman Britain are well known and are able to be incorporated within an LCP calculation, the use of LCP analysis should be limited to predicting Roman roads in the Highland zone of Roman Britain, which are constrained by the topography, thus better predicted than Roman roads in the Lowland zone of Roman Britain. Furthermore, the use of flow maps to visualise the spatial distribution of the LCP accuracy was found to be an effective method for locating where the accuracy of the LCPs changed, and allowed for greater exploration of the results compared to previously used validation methods. Due to this, it is recommended that future LCP studies utilise flow maps, as this allows for a more granular investigation into the success of the LCPs, which can often be masked when single figures are given to describe the LCP.

Secondly, the assessment on the effects of the number of directions identified that the accuracy of the generated LCPs increased, and the worst case distance decreased, when using more directions in the LCP calculation, further suggesting that LCP computation should incorporate a minimum of 16 directions, as recommended by Herzog (2014b). Furthermore, custom software should be developed to allow for the use of 24 and 48 directions, with the LCPs compared and their effect on the accuracy assessed using the worst case distance method demonstrated in this thesis, which has been show to effectively quantify the effects of direction on the accuracy of LCPs. Similarly, the higher resolution OS Terrain 5 was found to generate LCPs that more accurately predicted the location of Roman roads in Roman Britain than the lower resolution SRTM. Therefore, this thesis suggests that higher resolution DEMs, which represents the topography more accurately, and generates more accurate LCPs, should be used when undertaking LCP analysis. However, it is recommended that if paleoenvironmental data is available, then the past terrain should be reconstructed, which Conolly and Lake (2006) states can enhance the understanding of the landscape. If not, then as recommended by Herzog and Yépez (2014), random variations should be introduced in the DEM, allowing for the stability of the LCP to be tested. Similarly, through comparing the results of multiple cost functions, this study also found that the most accurate cost function when reconstructing Roman roads in Roman Britain is the time based Modified Hiking cost function developed by Márquez-Pérez et al. (2017). The similarity of the Modified Hiking function to the more popular Tobler's Hiking Function suggests that both should be used, and compared, in future LCP analysis studies. Nonetheless, due to the accuracy of the LPCs being sensitive to the algorithm used (Mlekuž, 2014), it is recommended that future LCP analyses compare multiple cost functions and experiment by changing the values in cost functions in order to assess which computes the most accurate LCPs.

Lastly, the implementation of the Higuchi viewshed in the Gask Ridge and the Stanegate study area was found to be effective in determining whether the development of the Roman roads were influenced by the need for the roads to be visible from nearby fortlets. In addition, the success of the Higuchi viewshed suggests that the incorporation of the distance multipliers determined by Ogburn (2006) are appropriate when undertaking LCP analysis, and can be used to effectively elucidate whether visibility factors govern the construction of Roman roads in Roman Britain. Therefore, this study suggests that the use of Higuchi viewshed with Ogburn's (2006) distance multipliers should be used in LCP analyses that are exploring whether visibility was a factor in the creation of ancient roads.

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APPENDICES

Appendix A: Location of fortlets from the Digital Atlas of the Roman Empire (DARE, 2015)

Study area	Fortlet	Latitude	Longitude
Gask Ridge	Black Hill	284519.5752	710751.2311
	Shielhill South	284989.6563	711501.3652
	Shielhill North	285589.8837	712191.2483
	Westerton	287309.7201	714570.8697
	Parkneuk	291669.4358	718460.9969
	Raith	293189.7535	718521.6079
	Ardunie	294689.7033	718761.4365
	Roundlaw	295799.6976	718891.0737
	Kirkhill	296759.6967	718830.8844
	Muir o'Fauld	298209.8744	718970.7101
	Witch Knowe	299759.4921	719530.7049
	Moss Side	300781.9073	719925.3759
	Thorny Hill	302060.0876	720431.2964

Appendix B: R code for the calculation of the LCPs

```
install.packages("raster", repos='http://cran.rstudio.com/')
library(raster) # used for reading raster files
install.packages('gdistance',repos="http://R-Forge.R-project.org")
library(gdistance) # used for LCP analysis
install.packages("rgdal", repos='http://cran.rstudio.com/')
library(rgdal) # used to write shapefile
install.packages("sp", repos='http://cran.rstudio.com/')
library(sp) # used for data management of computed LCP

print("libraries installed and loaded")

setwd("/data_files/")

river_raster <- raster("river_raster.tif")
dtm_raster <-  raster("elevation.tif")
view <-  raster("higuchi_cs.tif")

## ----------------------- ##

# function to calculate altitude difference between cells
altDiff <- function(x){x[2] - x[1]}

directions <- 16 # denotes the number of directions by which differences in height
are calculated from the centre origin cell. This can also be 4 or 8, however
computational burden increases when using a greater number

# transition values of neighbouring cells
# symm is TRUE for isotropic cost functions, FALSE for anisotropic cost functions
hd <- transition(dtm_raster, altDiff, directions, symm=FALSE)

# difference in height between cell divided by the distance between cells

slope <- geoCorrection(hd)

adj <- adjacent(dtm_raster, cells=1:ncell(dtm_raster), pairs=TRUE, directions)

cost <- slope

# Tobler's 'Hiking Function' (Tobler, 1993)

# cost[adj] <- 6 * exp(-3.5 * abs(slope[adj] + 0.05)) # calculates speed of movement
between adjacent cells. Cost function as stated in van Etten (2017)

# Herzog's sixth polynomial (Herzog, 2010)
# cost function as stated in Nakoinz and Knitter (2016)

#cost[adj] <- 1 / ((((1337.8 * slope[adj]^6) + (278.19 * slope[adj]^5) - (517.39 *
slope[adj]^4) - (78.199 * slope[adj]^3) + (93.419 * slope[adj]^2) + (19.825 *
slope[adj]) + 1.64))) # calculates energy usage between adjacent cells
```

```r
# Modified Hiking Function (Márquez-Pérez et al., 2017)
# cost function based on Márquez-Pérez et al. (2017)

#cost[adj] <- (4.8 * exp(-5.3 * abs((slope[adj] * 0.7) + 0.03))) # calculates speed of movement between adjacent cells.

## ----------------------- ##

river_cs <- transition(river_raster, transitionFunction = mean,directions = 16, symm=TRUE)
# neighbouring cell values are averaged by using mean in transistionFunction

## ----------------------- ##

view_cs <- transition(view, transitionFunction = mean, 16, symm=TRUE)
# neighbouring cell values are averaged by using mean in transistionFunction

## ----------------------- ##

# cost surfaces combined to create final cost surface
combined_cs <- (cost * view_cs) * river_cs

# correct for diagonal cell connections
Conductance <- geoCorrection(combined_cs)

## ----------------------- ##

# example origin and destination points for Gask Ridge (i.e., Ardoch and Thorny Hill)
pts <- cbind(x=c(284086.308, 302533.3382), y=c(710010.5934,720602.4104))

# calculate the shortest path from the origin coordinate point to the destination coordinate point
AtoB <- shortestPath(Conductance, pts[1,], pts[2,], output="SpatialLines")

# conversion to a SpatialLinesDataFrame object
AtoBdf <-SpatialLinesDataFrame(AtoB, data.frame(id=1:length(AtoB)))

# saved as an ESRI Shapefile
writeOGR(AtoBdf, dsn="", layer="LCP" ,driver="ESRI Shapefile")
```

Appendix C: R code for the plotting of the LCP flow maps

```
library(rgdal) # used to read shapefiles
library(ggplot2) # used to plot graph

setwd("/data_files/") # set working directory

margary_road <- readOGR("road_vertices.shp") # vertices of the predicted LCP
fortlet <- readOGR("gask_fortlets.shp") # fortlets locations
fort <- readOGR("gask_forts.shp") # fort locations
distance <- read.csv("distances_from_road.csv") # distances from LCP vertices to
Roman road

fortlet_df <- as.data.frame(fortlet) # convert to dataframe in order to use coordinates
for plotting
fort_df <- as.data.frame(fort) # convert to dataframe in order to use coordinates for
plotting

graph <- ggplot(margary_road, aes(x=long, y=lat))

graph  + theme_grey() + geom_point(aes(size=distance$NEAR_DIST,
colour=distance$NEAR_DIST < 250)) + scale_size_area()  + xlab("Longitude") +
ylab("Latitude") + labs(size = "Distance from predicted LCP to known\nMargary 9a
and 9b Roman road (m)",colour = "Distance from predicted LCP to known\nMargary
9a and 9b Roman road below 250m") + geom_point(data = fortlet_df, aes(x=
fortlet_df $coords.x1, y= fortlet_df$coords.x2), shape=15, size=1, colour="black") +
geom_point(data = fort_df, aes(x= fort_df $coords.x1, y= fort_df $coords.x2),
shape=15, size=2, colour="black") + annotate("text", x = 283955.7, y = 709935.8 -
200, label = "Ardoch") + annotate("text", x = 289754.2 + 850, y = 718064.6 - 100,
label = "Strageath") + annotate("text", x = 302060.1 + 400, y = 720431.3 - 200, label
= "Thorny Hill") + annotate("text", x = 284519.5752 + 700, y = 710751.2311, label =
"Black Hill") +
annotate("text", x = 284989.6563 + 1100, y = 711501.3652, label = "Shielhill South")
+ annotate("text", x = 285589.8837 + 1100, y = 712191.2483, label = "Shielhill
North") + annotate("text", x = 286083.7777 + 1200, y = 712944.8657, label = "Kaims
Castle") + annotate("text", x = 287309.7201 + 800, y = 714570.8697, label =
"Westerton") + annotate("text", x = 291669.4358, y = 718460.9969 - 200, label =
"Parkneuk") +
annotate("text", x = 293189.7535, y = 718521.6079 - 200, label = "Raith") +
annotate("text", x = 294689.7033, y = 718761.4365 - 200, label = "Ardunie") +
annotate("text", x = 295799.6976, y = 718891.0737 - 120, label = "Roundlaw") +
  annotate("text", x = 296759.6967, y = 718830.8844 - 300, label = "Kirkhill") +
  annotate("text", x = 298209.8744, y = 718970.7101 - 200, label = "Muir o'Fauld") +
  annotate("text", x = 299759.4921, y = 719530.7049 - 200, label = "Witch Knowe") +
  annotate("text", x = 300781.9073, y = 719925.3759 - 300, label = "Moss Side")
```